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THESIS

INCREASING RANGE AND LETHALITY OF EXTENDED-RANGE MUNITIONS (ERMS) USING NUMERICAL WEATHER PREDICTION (NWP) AND THE AUV WORKBENCH TO COMPUTE A BALLISTIC CORRECTION (BALCOR)

by

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December 2006

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13. ABSTRACT (maximum 200 words)

Extended-Range Munitions (ERMs) are gun-launched rocket-boosted munitions having an effective range over 27 km. In accordance with Sea Power 21 and the Marine Corps' requirements for sea-based fire support, three ERMs are being developed. The purpose of this work is to increase the range and lethality of these munitions by applying environmental effects when computing the projectiles' trajectory.

A broad review of artillery and munitions literature reveals that historically 66% of ballistic error can be attributed to meteorological factors. The most important factors are wind (speed and direction), temperature, and pressure. It has also been shown that global atmospheric numerical weather prediction (NWP) data typically outperforms the traditional radiosonde data and is suitable for use in ballistic corrections.

Forecasted NWP products provided by the Fleet Numerical Meteorology and Oceanographic Center (FNMOC) are integrated using the Joint Meteorology and Oceanographic (METOC) Broker Language (JMBL) into a Five-Degree of Freedom (5DOF) aerodynamic model within the Autonomous Unmanned Vehicle (AUV) Workbench producing a ballistic correction (BALCOR) for the munition. This new capability can significantly enhance naval gunfire effectiveness since the BALCOR increase the munitions' range and the ability apply kinetic energy onto the target rather than using it to maneuver to the target.

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LIST OF ACRONYMS AND ABBREVIATIONS

2D	two dimensional
3D	three dimensional
3DVAR	3-dimensional variational
ABL	Allegheny Ballistics Laboratory
ACAT	acquisition category
AFATDS	advanced field artillery tactical data system
AFB	Air Force Base
AFWA	Air Force Weather Agency
AGS	advanced gun system
ANGLICO	Air/Naval Gunfire Liaison Companies
ANSR	autonomous naval support round
APG	Aberdeen Proving Ground
API	application program interface
ARDEC	Army Armament Research, Development, and Engineering Center
ARS	ammunition recognition system
ARL	Army Research Laboratory
ASCII	American standard code for information interchange
ASW	Antisubmarine warfare
ATK	Alliant Technical Systems Inc.
ATO	air tasking order
AUV	autonomous unmanned vehicle
AVCL	autonomous vehicle control language

AVLS	advanced vertical launch system
AWS	Air Weather Service
BACIMO	battlespace atmospheric and cloud impacts on military operations
BAE	BAE Systems, a combination of British Aerospace (BAe) and Marconi Electronic Systems (MES)
BAA	broad agency announcement
BALCOR	ballistic correction
BALPARS	ballistic parameters
BALW	ballistic winds
BDS	binary data section
BFM	battlescale forecast model
BIW	Bath Iron Works Shipyard
BRL	Ballistic Research Laboratory
BMS	bit-map section
BTERM	ballistic trajectory extended range munition
CAES	Custom Analytical Engineering Systems
CAPS	Center for Analysis and Prediction of Storms
CE	chemical energy
CEP	circular error probability
CG	center of gravity
CMetS	computerized meteorological system
CMM	computer MET messages
CNMOC	Commander Naval Meteorology and Oceanography Command
CNO	Chief of Naval Operations

COAMPS	coupled ocean atmosphere mesoscale prediction system
cps	calculations per second
CS-DL	Charles Stark Draper Laboratory
CTF	Commander, Third Fleet
DD	destroyer
DDG	guided missile destroyer
DMSP	Defense Meteorological Satellite Program
DMZ	demilitarized zone
DOD	Department of Defense
DOF	degree of freedom
DPICM	dual-purpose improved conventional munition
EDM	engineering and manufacturing development
EMRG	electromagnetic rail gun
ENIAC	electronic numerical integrator and computer
ERGM	extended range guided munition
ERM	extended range munition
EW	electronic warfare
EWTGPAC	Expeditionary Warfare Training Group, Pacific
F	Fahrenheit
FAA	Federal Aviation Administration
FACSFACSD	Fleet Area Control and Surveillance Facility, San Diego
FCS	fire-control system
FCMMs	forecast MET models
FIREX	fire exercise

FNMOC	Fleet Numerical Meteorology and Oceanographic Center
FOUO	for official use only
FTAB	Firing Tables and Ballistic Division
FY	fiscal year
G	gravitational force
GDS	grid description section
GIF	guidance-integrated fuze
GIG	global information grid
GLOBE	global land one-kilometer base elevation
GPS	global positioning system
GRIB	gridded binary data format
GTL	gun target line
GTRAJ3	general trajectory model, version 3
GWS	gun weapon system
HARM	high-speed anti-radiation missile
hr	hour
IAS	Institute for Advanced Study
IEEE	Institute of Electrical and Electronics Engineers, Inc
IMU	internal measurement unit
INS	inertial navigation system
IOC	initial operational capability
IPS	integrated power system
ISD	ignition safety device
ISIS	integrated stored information system

j	Joule
J2EE	Java 2 platform, enterprise edition
JMBL	joint METOC broker language
JMDSF	joint METOC data services framework
JNWPU	Joint Numerical Weather Prediction Unit
K	Kelvin
KE	kinetic energy
kg	kilogram
km	kilometer
lbs	pounds
LHA	general-purpose amphibious assault ships
LM	Lockheed Martin
LPD	landing platform dock
LRLAP	long-range land attack projectile
LRP	long-range projectile
LUT	limited user test
m	meter
Ma	Mach number
MAC	Military Airlift Command
MATT	met-along-the-trajectory
MET	meteorology
METOC	meteorology and oceanography
mm	millimeter
MMP	massively parallel processor

MFVSR	multi-function volume search radar
MINEX	mine exercise
MIRV	multiple independently-targeted reentry vehicles
MJ	megajoules
MK	mark
MNF	multinational force
MOD	modification
MOS	model output statistics
MSL	mean sea level
MSLP	mean sea level pressure
MVOI	multivariate optimum interpolation system
NANWEP	Navy Numerical Weather Project
NASA	National Aeronautics and Space Administration
NASNI	Naval Air Station North Island
NATO	North Atlantic Treaty Organization
NAVDAS	atmospheric variational data assimilation system
NCAR	National Center for Atmospheric Research
NCEP	Nation Centers for Environmental Prediction
NG	Northrop Grumman
NGFS	naval gunfire support
nm	nautical mile
NMC	National Meteorological Center
NOGAPS	Navy Operational Global Atmospheric Prediction System
NOAA	National Oceanic and Atmospheric Administration

NPS	Naval Postgraduate School
NRL/MRY	Naval Research Laboratory, Monterey Detachment
NSWC-DD	Naval Surface Warfare Center, Dahlgren Division
NSW	National Weather Service
NWP	numerical weather prediction
OIF	Operation Iraq Freedom
OMFTS	Operational Maneuver from the Sea
ONR	Office of Naval Research
OOP	object-oriented programming
OSS	optical sight system
OTH-T	over-the-horizon targeting
PDS	product definition section
PEO IWS	Program Executive Office, Integrated Weapons Systems
PE	potential energy
PVLS	peripheral vertical launch system
q	dynamic pressure
R	gas constant
rad	radian
RAOBs	radiosonde balloon obervations
RCMMs	RAOBS Forecasted MET Models
RDAP	reliability determination/assurance program
RFP	request for proposal
rho	density
RIFT	Raytheon Field Integration Team

RMS	Raytheon Missile Systems
ROC	range operations center
s	second
SADARM	sense and destroy armor
SAIC	Science Applications International Corporation
SBU	special boat unit
SCI	San Clemente Island
SCORE	southern California offshore range
SDD	software design document
SEAL	sea air land
SEALORDS	Southeast Asia lake, ocean, river, and delta strategy
SGI	Silicon Graphics, Inc
SHOBA	shore bombardment area
SIMNET	simulations networking system
SLBM	submarine launched ballistic missile
SOAP	simple object access protocol
SSG	strategic studies group
SSM/I	special senor microwave imager
STA	surface-to-air
STRIKEX	strike exercise
STS	surface-to-surface
T	temperature
TACFIRE	tactical fire
TDA	tactical decision aid

TEB	total energy budget
TOF	time of flight
UAV	unmanned aerial vehicle
UCS	universal character set
UDI	United Defense Industry
UK	United Kingdom
URL	uniform resource locator
U.S.	United States
USMC	United States Marine Corps
VGAS	vertical gun for advanced ships
VRML	virtual reality modeling language
WMO	World Meteorological Organization
WWI	World War I
WWII	World War II
WRF	weather research and forecast
WSMR	White Sands missile range
WWW	World Wide Web
X3D	extensible 3D graphic standard
XML	extensible markup language
XSBC	XML schema-based binary compression
XTC	XML based tactical chat
YPG	Yuma Proving Grounds

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I. INTRODUCTION

A. OVERVIEW

This thesis supports the ongoing development of Extended-Range Munitions (ERMs) which will have an effective firing range of 28 kilometers (km) (15 nautical miles) or greater. These projectiles are required to bridge the gap in long-range Naval Gunfire Support (NGFS) that has existed since the retirement of the U.S. Navy's battleships. The purpose of this thesis is to improve the lethality and range of ERMs.

Lethality can be improved by applying environmental affects to the projectile's trajectory and calculating a ballistic correction (BALCOR) for the firing solution thereby increasing the amount of kinetic energy (KE) it can transfer to the target. When a projectile is fired, it has three types of destruction energy: chemical energy (CE) contained in explosive warhead, KE and potential energy (PE). When a projectile strikes its intended target, all of these energies are transferred to it. The projectile has its maximum PE at the apogee and as the projectile maneuvers to its target it must convert this PE to KE. If a ballistic correction can produce an optimal flight path, the projectile retains more energy in the form of velocity to strike its target. In some cases, pre-flight BALCORs might extend the range of an ERM or in a worse-case scenario ensure that the ERM has enough energy to reach its otherwise unattainable target.

In the course of this research, a high-fidelity simulation is presented using a Five-Degree of Flight (5DOF) aerodynamics model for the projectile's flight path. Forecasted weather data provided by Fleet Numerical Meteorology and Oceanographic Center (FNMOC) is applied to the 5DOF to improve targeting and accuracy by calculating the ballistic correction.

Defense contractors for the U.S. Navy are currently developing three ERMs that are in the final stages of development. These projectiles are the Extended-Range Guided Munition (ERGM), the Ballistic Trajectory Extended-Range Munition (BTERM), and the Long-Range Land Attack Projectile (LRLAP). The ERGM and BTERM will be deployed on U.S. Navy cruisers and destroyers utilizing a MK 45 5-inch/54 caliber Gun Weapon System (GWS) upgraded to the MK 45 5-inch/62 caliber GWS. The LRLAP will be deployed on the navy's future destroyer – the DD-1000, formerly the DDX – and is concurrently being developed with the Advanced Gun System (AGS).

B. DISCUSSION

When the U.S. Navy retired its battleships in the early 1990s, it lost its capability to provide fire support for maneuvers ashore at a range greater than 22 km (12 nm). As the United States Marine Corps (USMC) doctrine has evolved, it has focused on an expeditionary maneuver force based on ship-to-objective movement requiring sustained, long-range fire support. However, the U.S. Navy's current Mk 45 5-inch guns, air support, and Tomahawk cruise missiles cannot provide a sufficient volume of fire at a reasonable cost to support projected amphibious and near shore operations (Kime, 2004).

C. MOTIVATION

Meteorological effects have influenced the battlefield in modern times from the scheduling of the D-Day invasion to the use the weapons in Desert Storm. Operationally, such concerns remain relevant when fighting in close quarters, such as an urban environment, where the political ramifications of unintended collateral damage and fratricide have put increased pressure on the warfighter's ability to safely and precisely hit a target with the first shot.

The motivation for this thesis is to use meteorological knowledge of the environment to support the warfighter. This supports the Commander Naval Meteorology and Oceanography Command's (CNMOC) *Battlespace on Demand: Commander's Intent* (McGee, 2006). It provides the warfighter a competitive edge through leveraging meteorology knowledge and directly applying it to a weapon system at the operational level.

Environmental effects have a direct impact on the ability of weapons to reach their intended target. One example of this impact was during the dust storm that took place on the fifth day of combat operations during Operation IRAQI FREEDOM (OIF) and nearly halted advances by coalition forces. This dust storm impacted ground and air operations across the entire theater and delayed the impending attack on the Iraqi capital. Military meteorologists were able to use local and numerical model output to forecast this storm and assist military planners in planning for the effects of this storm. As a result of this forecast guidance, mission planners were able to "front load" Air Tasking Orders

(ATO) with extra sorties prior to the onset of the dust storm, and were able to make changes to planned weapons loads, favoring GPS-guided munitions over laser guided munitions (Anderson, 2004).

The increasing availability of accurate numerical weather prediction (NWP) in combination with advanced modeling, simulations, and visualization techniques will continue to improve warfighter capabilities. Environmental predictions, effects, and tactical applications will continue to grow as they become a mainstream component of the Global Information Grid (GIG) and net-centric warfare.

D. APPROACH TAKEN

In order for this thesis to demonstrate a realistic capability, a high-fidelity 5DOF aerodynamics model of an ERM was assessed and integrated with robotic modeling and simulation software. Once this simulation was developed, the effects of various environmental factors on the round were investigated. Next, the Joint METOC Broker Language (JMBL) a specific Meteorology and Oceanography (METOC) based Extensible Markup Language (XML) was used to extract FNMOC forecasted weather data from their weather forecast models along the projectiles' trajectory. These data are then transferred to the application that applies these weather parameters thereby calculating a BALCOR. Two plots of the projectiles' trajectory are compared: the straight projectile with no environmental factors except the U.S. Standard Atmosphere, 1976, and one with the environmental factors applied. The difference in distance and direction between the impact points and the range between the firing unit and the target provide the BALCOR. In order to compute a measure of effectiveness (MOE), the PE and KE are calculated for the projectile at both the apogee and impact point.

The 5DOF model was first developed in MATLAB using dynamic equations describing the basic laws of physics. After the base model was developed, it was translated into Java source code and incrementally improved with defense contractor assistance until it was a 5DOF representative of an ERM. Further information concerning the development of the 5DOF is for official use only (FOUO) and can be found in *Modeling Extended-Range Munitions (ERMs) in the Autonomous Unmanned Vehicle (AUV) Workbench* (Wahl, 2006) available at the Naval Postgraduate School (NPS).

E. THESIS ORGANIZATION

This thesis develops a process to apply forecasted environmental meteorological effects occurring along a projectile's trajectory by incorporating these effects into the projectile's high-fidelity 5DOF model. It builds upon the work created in *Modeling Extended-Range Munitions (ERMs) in the Autonomous Unmanned Vehicle (AUV) Workbench* (Wahl, 2006), where a 5DOF simulation was created using the Java programming Language. When the trajectory characteristics of range, apogee, and time of flight were compared to open-source BTERM data, the greatest parameter error was found to be less than eight percent.

Chapter II reviews the requirements for ERMs, a history of long-range projectiles (LRPs), history of computing projectile ballistics, ERMs under development, and related equipment. Chapter III covers the development of NWP, NWP centers, NWP models, and studies concerning the environmental effects on munitions. Chapter IV examines ERM 5 degree of freedom (5DOF) dynamic modeling and uses it to examine its sensitivity to NWP model output error. Chapter V covers current ballistic forecast models, methods of communicating NWP data, methods of the ballistic information, simulation model, an analysis and design of the ERM model, and standards of interoperability. Chapter VI presents the BALCOR results computed during simulations experiments. Chapter VII presents conclusions, recommendations for future research, and discusses possible uses for this technology in other projectile applications. Appendix A contains a screenshot of the AUV Workbench after it has computed a BALCOR.

II. BACKGROUND AND RELATED WORK

A. INTRODUCTION

This chapter has been duplicated from *Modeling Extended-Range Munitions (ERMS) in the Autonomous Unmanned Vehicle (AUV) Workbench* (Wahl, 2006) for the reader's convenience. The information contained in this chapter is derived from sources openly available to the public.

This chapter outlines the requirements for ERMs, provides the history of long-range projectiles back to World War I (WWI) and the history of computing projectile ballistics while summarizing ERMs currently under development by defense contractors in the United States, and briefly describes ERM-related equipment.

B. OVERVIEW OF EXTENDED-RANGE MUNITIONS (ERMS)

In general, all ERMs operate similarly. The projectile is fired out of a gun providing its initial kinetic energy. A short time after exiting the gun barrel, the projectile's stabilizing fins deploy and a solid-propellant rocket motor ignites, providing additional boost. As the round flies to its apogee, its guidance package activates and searches for Global Positioning System (GPS) satellites while its steering canards deploy, stabilizing the round. Once the round reaches apogee and has acquired a GPS signal, its guidance system uses the steering canards to fly or glide the round directly to its target.

For the purpose of this thesis, ERMs are munitions that are rocket-boosted and use a GPS guidance system, while long-range projectiles (LRPs) receive all of their kinetic energy in the gun barrel and have no guidance systems.

C. REQUIREMENTS FOR EXTENDED-RANGE MUNITIONS (ERM)

1. Marine Corps Requirement

Future Extended-Range Naval Gunfire Support (NGFS) is a critical enabler of the Marine Corps' *Operational Maneuver from the Sea* (OMFTS) (Krulak, n.d.). Extended-range naval gunfire is expected to provide critical stand-off fire support for marine units maneuvering ashore. OMFTS provides a concept for the projection of naval power ashore that requires naval ships to provide fire support to marine units operating in the littoral regions and near-shore areas. In OMFTS, the commandant of the Marine Corps calls for the U.S. Navy to provide effective fire from forces afloat with the ability to deliver fires with increased range and improved accuracy and lethality (Krulak, n.d.). The Marine Corps has set a range of 370 km (200 nm) as a requirement for NGFS (*Naval Surface Fire Support Program Plans and Costs*, 1999).

2. Chief of Naval Operations (CNO) Directive

The CNO outlines his vision for the U.S. Navy's future capabilities in *Sea Power 21*. In this document, the three core capabilities for the future navy are identified: Sea Strike, Sea Shield, and Sea Basing. Sea Shield develops naval capabilities related to homeland defense, sea control, assured access, and projecting defense overland; Sea Strike is a broadened concept for naval power projection that leverages precision, stealth, and endurance to increase operational tempo, reach, and effectiveness; the Sea Base projects the sovereignty of the United States globally while providing Joint Force Commanders with vital command and control, fire support, and logistics from the sea; and FORCEnet is an overarching effort to integrate warriors, sensors, networks, command and control, platforms, and weapons into a fully netted, combat force making network-centric warfare an operational reality (Clark, 2002). Extended-Range NGFS has the capability to play an important role in all three of these capabilities with the support of FORCEnet.

The U.S. Navy currently has three fire-support options to strike targets ashore: cruise missiles, naval gunfire, and both manned and unmanned aircraft. Missiles have the greatest range and lowest risk to personnel, but are expensive and are in limited supply. Naval gunfire currently has a limited range of 22 km (12 nm), which puts the supporting platforms at great risk requiring them to operate close to the shoreline. Currently, aviation meets a majority of the power projection ashore, but these aircraft must be supported from either land bases or aircraft carriers. The employment of aviation assents from land bases can be complicated by over flight treaties, refueling, and pilot fatigue, while carrier aviation is limited by environmental factors such as sea state, visibility, and winds; maneuverability; and underway replenishment. Recent fire-support studies by the CNO's Strategic Studies Group (SSG) determined that "a combination of guns and missiles with guns applied to the majority of the target sets is the most cost-effective solution" (Adams, 2003). These studies concluded that that extended-range precision NGFS might provide a revolutionary improvement in sustained firepower capacity.

a. Sea Strike

The CNO's outline of Sea Strike specifically addresses the need for Extended-Range NGFS to project decisive combat power ashore. As previously noted, all three of the U.S. Navy's methods of providing this combat power have limitations. The short 22 kilometer (12 mile) effective range limits the current 5-inch/54 caliber MK 45 Gun Weapon System (GWS). The ERGM and BTERM projectiles fired from an upgraded MK 45 5-inch/62 caliber GWS will extend range of surface fires to 111 km (60 nm). The AGS/LRLAP GWS further extends the effective range of NGFS to over 148 km (80 nm). Sea Strike's action steps include developing, acquiring, and integrating systems to increase combat reach, stealth, and lethality (Clark, 2002). The ERGM and BTERM Mk 45 5-inch/62 caliber GWS and the LRLAP/AGS fulfill this action step.

b. Sea Shield

Sea Shield addresses the protection of the homeland and national interests with a layered global defensive power. This power is based on sea control and a forward presence, which are needed to assure access to contested littorals and project defensive power deep inland. As with Sea Strike, the foundation of these integrated operations will be information superiority, total force networking, and an agile and flexible sea-based force (Clark, 2002).

The littoral regions of a hostile power are a dangerous place to conduct naval operations. One of the action steps of Sea Shield is to expand combat reach from the sea; again, the ERGM, BTERM, and AGS/LRLAP fulfill this action step. The littoral zone can contain many hazards to surface ships: mines - which are cheap, easy to deploy, and hard to detect; suicide boats; land launched anti-ship missiles; and diesel submarines. Increasing the standoff range of naval fire support platforms decreases this vulnerability and increases survivability (Clark, 2002).

c. Sea Basing

Operational maneuvers have always been and always will be fundamental to military success. In future warfare, the extended reach of networked weapons and sensors will tremendously increase the impact of naval forces in joint campaigns. This is achievable by exploiting the largest maneuver area on the face of the earth: the sea. Sea

Basing serves as the foundation from which offensive and defensive fires are projected making Sea Strike and Sea Shield realities (Clark, 2002).

d. FORCEnet

FORCEnet is the "glue" that binds together Sea Strike, Sea Shield, and Sea Basing. It is the operational construct and architectural framework for naval warfare in the information age. It integrates warriors, sensors, command and control, platforms, and weapons into a networked, distributed combat force. FORCEnet is the manner in which data can be shared within the force (Clark, 2002).

D. HISTORY OF LONG-RANGE PROJECTILES (LRPS)

1. World War I (WWI)

a. Paris Gun

The history of long-range gunfire began with the German Army during WWI. During the war, the Germans built three ‘Paris’ Guns that were used to shell Paris between March and August of 1918. These guns were rail-mounted, weighed 256 tons, and had a 28 meter, 210 millimeter caliber rifled barrel with a 6 meter smoothbore extension (Darling, n.d.; Eisenstein, 2004). At the time, the Paris Gun was a weapon like no other, capable of firing a 94 Kg projectile over 30 km with a ballistic flight apogee of 40 km. At the start of its 170 second trajectory, each shell from the Paris Gun reached a speed of 1,600 km/s or about five times the speed of sound (Darling, n.d.). Unfortunately, the gun’s barrel did not hold up well and after firing 65 projectiles, each of which had a progressively larger caliber to allow for barrel wear, the barrel had to be rebored.

The purpose this gun was not to destroy Paris, as it was too inaccurate, but to devastate the morale of the Parisians. From March through August of 1918, three Paris guns fired 351 projectiles from the woods of Crepy, killing 256 and wounding 620 Parisians (Darling, n.d.). As a tactical military weapon, the guns were not effective due to their small payloads, regular requirement to rebore the barrel, and their inaccuracy. However, as a strategic weapon, the Paris guns did serve well as a psychological tool and greatly demoralized the inhabitants of Paris.

2. World War II (WWII)

a. Gustav Gun

At the onset of WWII, Adolf Hitler wanted a gun to use to attack the French Maginot line along the German-French boarder. He required that the gun be able to pierce a meter of steel, seven meters of concrete, or thirty meters of dense earth (Eisenstein, 2004). Thus, two Gustav Guns (the 'Gustav' and the 'Dora') were built. These guns were massive, as seen in Figure 1, weighing 1,344,000 kg (1344 tons), standing 16 m (52 ft) tall, 6 m (20 ft) wide, 43 m (140 ft) long and were crewed by over 500 soldiers (Eisenstein, 2004).

Figure 1. The German Gustav Gun was so large special railroad tracks had to be laid to move the weapon (From Eisenstein, 2004).

These guns had a 800 millimeter (mm) (31 in) bore and fired two projectiles: a 4,800 Kg (10,584 lb) high-explosive shell and a 7,502 Kg (16,540 lb) concrete-piercing shell and might hit a target up to 47 km (29 miles) away (Eisenstein, 2004). Early in the war, the Dora was destroyed by the German to prevent its capture by the Russians. The Gustav saw action in two engagements: the assault on the Soviet cities of Sevastopol and Warsaw, where it fired 300 and 30 projectiles respectively and was captured and destroyed at the end of the war by U.S. forces (Eisenstein, 2004).

b. Battleships

The Battleships are the most famous and effective long-range NGFS platforms and came into service during WWII. The Battleships first saw action in the Pacific War and were used for both shore bombardment and as carrier escorts. Each battleship was equipped with nine 16-inch guns that fired two types of projectiles: armor-piercing and high-capacity explosive projectiles. The armor-piercing projectile weighed 1,225 kilograms (kg) (2,700 pounds (lbs)) and had a range of 39 km (21 nm), while the high capacity explosive projectiles weighed 408 kg (900 lbs) and had a range of 42.6 km (23 nm) (*New Jersey (BB 62),* n.d.). Each gun had the capacity to fire one round every thirty seconds.

During the war battleships filled many missions, serving as escorts for high value units such as aircraft carriers, NGFS platforms for shore bombardment, and flagships for squadron commanders. The surrender of Japan took place on the deck of the USS Missouri (BB 63) on September 2, 1945 (Figure 2). After the war, most of the battleships were decommissioned.

Figure 2. Fleet Admiral Nimitz signs the Japanese surrender Agreement on board the USS Missouri (BB 63) (From *Formal Surrender of Japan, 2 September 1945.,* 1999)

Name	Hull Number	Commission Dates	Decommission Dates	Fate
North Carolina	55	9 Apr 1941	27 Jun 1947	Transferred to the state of North Carolina 6 September 1961.
Washington	56	15 May 1941	27 Jun 1947	Sold for scrap 24 May 1961.
South Dakota	57	20 Mar 1942	31 Jan 1947	Sold for scrap 25 October 1962.
Indiana	58	30 Apr 1942	11 Sep 1947	Sold for scrap 1 June 1962.
Massachusetts	59	12 May 1942	27 Mar 1947	Transferred to the state of Massachusetts 8 June 1965.
Alabama	60	16 Aug 1942	9 Jan 1947	Transferred to the state of Alabama 16 June 1964.
Iowa	61	22 Feb 1943 25 Aug 1951 28 Apr 1984	24 Mar 1949 24 Feb 1958 26 Oct 1990	Berthed in Suisan Bay, San Francisco, CA, 21 April 2001.
New Jersey	62	23 May 1943 21 Nov 1950 6 Apr 1968 28 Dec 1982	30 Jun 1948 21 Aug 1957 17 Dec 1969 8 Feb 1991	Transferred to the state of New Jersey 20 January 2000.
Missouri	63	11 Jun 1944 10 May 1986	26 Feb 1955 31 Mar 1992	Opened as a museum 29 January 1999, at Arizona Memorial Pearl Harbor, HI.
Wisconsin	64	16 Apr 1944 3 Mar 1951 22 Oct 1988	1 Jul 1948 8 Mar 1958 30 Sep 1991	Moored at the National Maritime Center, Norfolk, VA, on 16 April 2001.

Table 1. List of the battleships that were commissioned and fought in WWII. (After Chief of Naval Information, 2001)

3. Korea

When the Korean War began, all but one battleship, the USS Missouri, had been decommissioned (*USS Missouri (BB 63), n.d.*). During the course of the war, the need for NGFS was so great, that the USS Iowa (BB 61), USS New Jersey (BB 62), and USS Wisconsin (BB 64) were all recommissioned back into service in 1950 (*USS New Jersey (BB 62)*, 2003). During the war, the battleships were extensively used for shore bombardment in support of North Atlantic Treaty Organization (NATO) operations. After the war, they were again decommissioned.

4. Vietnam

Following the Tonkin Gulf Incident U.S. Naval forces in Vietnam were assigned to the following major operations: Operation Market Time (1965), Operation Sea Dragon (1966), and Operation SEALORDS (1968).

Vietnam was ideal for NGFS as the country's coastline is boarded by thin beaches and swamps that are have deep navigable waters right of shore allowing cruisers and destroyers to operate as close as a mile of the shoreline. Due to the dense interior jungle, Vietnam was highly dependent on its coastal waters sea as a means of commerce and traveling between villages and towns and as a result many of the enemy's activities, are near the coast and within easy range of naval guns (Kristiansen, n.d.; Marolda & Pryce, 1984).

Operation Market Time commenced in 1965 when U.S. Navy destroyers and U.S. Coast Guard cutters were assigned to coastal surveillance operations. Market Time was an attempt to form a coastal barrier patrol preventing the infiltration of men and supplies from Communist North Vietnam. Market Time forces also provided NGFS for smaller American and Vietnamese coastal patrol ships and ground units.

NGFS was most active and played a critical role in Operation Sea Dragon, which commenced in 1966 in an attempt to cut the lines of communications between the North and South Vietnamese. Sea Dragon used NGFS to destroy Vietcong land targets (bridges, roads, ferry landings, etc) and intercept water borne logistic craft (Greenberg, n.d.).

During Operation Sea Dragon, navy destroyers operated close to the Vietnamese coastline and engaged coastal shipping, coastal defense batteries, and targets of opportunity (Greenberg, n.d.). By the end of the initial phase of Sea Dragon, 1,554 5-inch projectiles were used to sink approximately 195 watercraft and engage coastal artillery and antiaircraft sites without the loss of or damage to a single ship or sailor (Greenberg, n.d.). By the end of the 1967, Operation Sea Dragon had expended 500,000 projectiles (rockets, mortars, and 5-inch rounds) and accounted for 382 watercraft destroyed and 325 damaged, five coastal defense batteries destroyed and two damaged, and two radar sites destroyed with another two damaged (Marolda, & Pryce, 1984;

Operation Sea Dragon, n.d.). Sea Dragon assets were also used to support U.S. Marine amphibious landings and ground sweeps in the southern part of the Demilitarized Zone (DMZ).

Operation	Year	Projectiles Fired	Damage
Market Time	1965	90,000	Enemy structure damaged: 4,000 Watercraft: 66 destroyed Estimated casualties: 3,000
Sea Dragon	1966	500,000 (including 1,554 5-inch rounds)	Enemy structure damaged: 35,000 Watercraft: 382 destroyed, 325 damaged Coastal Defense Sites: 5 destroyed, 2 damaged Radar sites: 2 destroyed, 2 damaged
SEALORDS	1968	454,000 (3,000 16-inch rounds)	Watercraft: 1,507 destroyed, 1,535 damaged Coastal Defense Sites: 75 destroyed, 268 damaged Estimated casualties: 2,000+ Plus the destruction or damage to numerous trucks, rail yards, bridges, storage sites, radar sites, and air defense sites.

Table 2. Estimated enemy damage per Vietnam Operations (After Greenberg, n.d.; Marolda & Pryce, 1984; *Battleship New Jersey,* n.d.; *Operation Sea Dragon,* n.d.).

In 1968, the USS New Jersey (BB 62) was brought back into service and was sent to Vietnam (*USS New Jersey (BB 62),* 2003). In the first two months on the gun line, the USS New Jersey (BB 62) fired over 3,000 16-inch projectiles at enemy targets (*Battleship New Jersey*, n.d.).

In 1968, the Tet Offensive interrupted Sea Dragon operations and all but two NGFS ships were sent to the gun line off the DMZ to provide gunfire support to Hue, Khe Sanh, and along the DMZ (Greenberg, n.d.). During its final year, Sea Dragon claimed 1,507 watercraft destroyed and 1,535 damaged; 75 coastal defense sites destroyed and 268 damaged; and destruction or heavy damage to numerous trucks, rail yards, bridges, storage sites, radar sites, and air defense sites (Greenberg, n.d.). Operation SEALORDS' (Southeast Asia Lake, Ocean, River, and Delta Strategy) objective was to suppress Viet Cong use of the maze of rivers and canals of the Mekong Delta region. Because these areas were often out of range of the Navy's 5-inch guns, NGFS did not play a critical role in Operation SEALORDS. The USS New Jersey (BB 62) with her large guns that had a longer range was used primarily for attacking the Ho Chi Min Trail and Northern Vietnam. When the Vietnam War ended, the USS New Jersey (BB 62) was redeployed to the United States and deactivated.

5. Iran-Iraq War

NGFS was used in the Iran-Iraq War during Operation Earnest Will between July 1987 and September 1988. In an attempt to deter the Iranians from attacking neutral shipping in the Persian Gulf, the United States registered eleven Kuwaiti tankers as American ships so they could legally be escorted by the U.S. Navy. The protection offered by American naval vessels, however, did not stop the Iranians, who used mines and small boats to harass the convoys transitioning the Gulf. To stop these attacks, the U.S. deployed several destroyers, Army helicopters, a Navy Sea Air Land (SEAL) Team, and a Special Boat Unit (SBU) to monitor and if required, put a stop to the Iranian hostile activity (*Operations Earnest Will, Prime Chance, Nimble Archer, and Praying Mantis 1987–1989.*, n.d.).

Operation Nimble Archer was launched in October 1987, as retaliation for an Iranian Silkworm missile attack on the reflagged tanker Sea Isle City that injured eighteen of its crewmembers. During Nimble Archer, four Navy Destroyers: USS Hoel (DDG 13), USS Leftwich (DD 984), USS Kidd (DD 661) and USS John Young (DD 973), shelled the two oil platforms in the Rostam oil field the Iranians were using as command and control bases. This attack was not very effective as it took over 1,000 5-inch high-explosive rounds to destroy the two platforms (*Operations Earnest Will, Prime Chance, Nimble Archer, and Praying Mantis 1987-1989.*, n.d.). On 14 April 1988, the USS Samuel B. Roberts (FFG 58) hit a mine, which tore a 30 by 23 ft hole in its hull and injured ten sailors. In retaliation, the Iranian frigate Sahalan and oil platforms in the Sirri and Sassan oil fields where shelled during Operation Praying Mantis by U.S. Navy destroyers (*Operations Earnest Will, Prime Chance, Nimble Archer, and Praying Mantis 1987–1989., n.d.)*.

6. Lebanon

In order to support the Lebanese Government and stop the fighting between religious factions, a Multinational Force (MNF), including 1,200 U.S. Marines, was sent into Lebanon in 1983. The mission of the MNF was to help stabilize the new Lebanese government and bolster their army. In August 1983, the Marines engaged Shiite Muslim and Druze Christian militias. During these engagements several Marines were killed and others wounded and in response, the USS Virginia (CGN-38) and USS John Rodgers (DD 983) shelled Shiite and Druze positions near Beirut (Frank, 1987).

In order to assist the Lebanese Army retain hold on the strategic Shouf Mountains village of Suq al Gharb, USS John Rodgers (DD 983), USS Radford (DD 968), and USS Virginia (CGN-38) fired 360 5-inch rounds (Friedman, 1989). A suicide attack destroyed the marine headquarters building at Beirut International airport killing 241 and wounded 70 marines and killing 58 French paratroopers. Later it was discovered that the suicide attack on the Marines was carried out by Iranians with the sponsorship of the Syrian government (Kelly, n.d.).

Marines also started to receive fire from Syrian occupied territory. Due to Syria's backing of anti-MNF fighters and downing of two American planes with Syrian surface-to-air missiles, the USS New Jersey (BB 63) fired on Syrian antiaircraft positions in the mountains of southeast Lebanon on December 14 and 15.

7. Gulf Wars

In the late 1980s the U.S. Navy built up to a 600-ship navy and, as previously noted, the USS Iowa (BB 61), USS Missouri (BB 63), USS New Jersey (BB 62), and USS Wisconsin (BB 64) were brought back into active duty. However, in early 1991, the USS Jersey (BB 63) and USS Iowa (BB 61) were again decommissioned.

The invasion of Kuwait by the Iraq Army in February of 1991 saved both the USS Missouri (BB 63) and USS Wisconsin (BB 64) from retirement. In February 1991, the Wisconsin's 16-inch guns provided NGFS for ground elements while they attacked targets north of Khafji (Saudi Arabia), Faylaka Island, and Kuwait City. Over a three-day period, Missouri bombarded Iraqi strongholds with 112 16-inch shells (*USS Missouri (BB 63),* n.d.).

Using an Unmanned Aerial Vehicle (AUV) as a spotter in combat for the first time, the Wisconsin attacked Iraqi targets and Iraqi boats previously used for raids along the Saudi coast and destroyed bunkers and artillery sites near Khafji. The two battleships alternated positions on the gun line and used their 16-inch guns to destroy enemy targets and soften defenses along the Kuwait coastline for a possible amphibious assault. The firepower of the battleships was so devastating that Iraqis surrendered to the battleship's AUV in the hope they would not incur the wrath of the 16-inch guns. After the liberation of Kuwait, the battleships were finally decommissioned in 1992, when it was deemed that they were too expensive to operate.

8. Operation Iraq Freedom (OIF)

Though two Air/Naval Gunfire Liaison Companies (ANGLICO) were deployed with British units during liberation of Iraq, NGFS was not used (Stan Coerr, personal communication, September 5, 2006).

E. HISTORY OF COMPUTING BALLISTICS: THE ELECTRONIC NUMERICAL INTEGRATOR AND COMPUTER (ENIAC)

The section is not copied from *Modeling Extended-Range Munitions (ERMS) in the Autonomous Unmanned Vehicle (AUV) Workbench* (Wahl, 2006) and is covered in greater depth in Chapter III.

F. EXTENDED-RANGE MUNITIONS (ERMS) UNDER DEVELOPMENT

1. Extended-Range Guided Munition (ERGM)

The development of the ERMs began in 1994, when the U.S. Navy contracted Raytheon to begin developing a long-range rocket-assisted, precision guided projectile for the MK 45 5-inch/54-caliber gun. The project eventually took on the title it has today: Extended-Range Guided Munition (ERGM). After two years of research and development, the Engineering and Manufacturing Development (EDM) phase began in July 1996 when the Navy awarded a contract to the Raytheon Company to develop and produce ERGM or EX-171 as a 'low cost' projectile capable of reaching 41 nm (Parsch, 2003).

The ERGM is a point target weapon that is fired from the 5-inch/62 caliber MK 45 Mod 4 Gun Mount. The ERGM incorporates a rocket motor, internal GPS, and an Inertial Navigation System (INS) to provide guidance and control illustrated in Figure 3. The round is fired at a predetermined, fixed target whose location is determined prior to firing. Once the round exits the barrel, eight stabilization fins deploy, five seconds later, the projectile's rocket-booster fires providing the increased boost allowing it to reach a flight apogee of 75,000 to 80,000 ft (Ripley, 2003). As the round travels to its flight apogee it deploys four control canards and its navigation system acquires up to 10 GPS satellites that it uses to correct is flight path allowing it to reach its intended target. As it enters its glide path phase, the round uses an internal measurement unit (IMU) and the GPS to 'fly' or 'glide' it to its intended target.

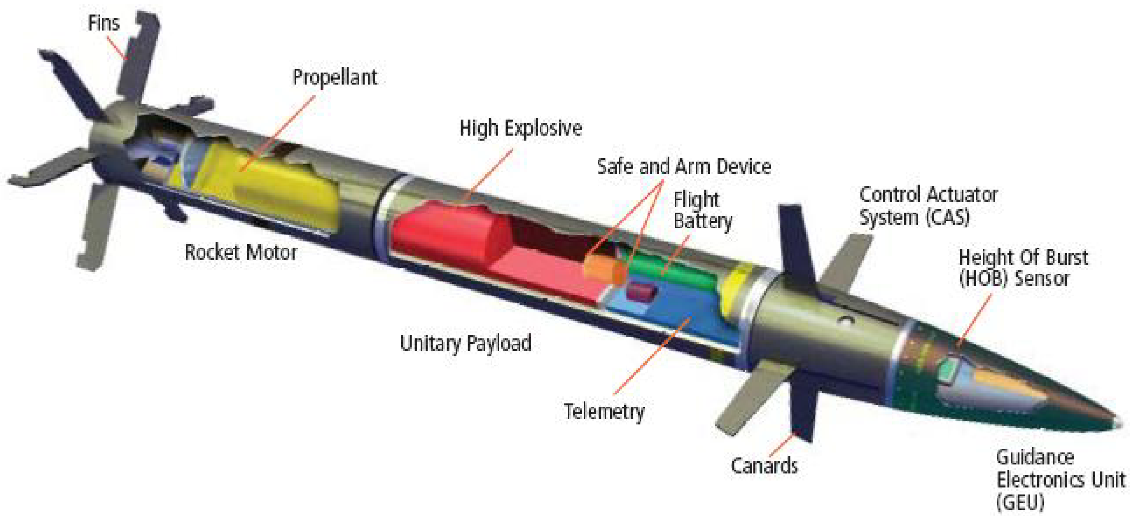

Figure 3. Cross section diagram of an ERGM munition (From ERGM, 2006).

The development of ERGM technology was more difficult than expected. Four difficulties arose during its development. The round guidance system had to be hardened to with stand the high gravitational force (G-force) of firing. The development of the canards for the projectile's aerodynamic design provided difficult. The development of the rocket motor capable of providing the in flight boost was challenging, and there was a requirement for a new, longer MK 45 5-inch/62 MOD 2 and MOD 4 (127 mm) caliber gun barrel that was capable of handling the higher firing energy required by the ERGM and still fire the standard 5-inch round.

Originally, it was planned to develop the ERGM with a unitary warhead and submunition package warhead, similar to that of a Tomahawk Cruise Missile. The initial warhead configuration for ERGM consisted of 72 EX-1 submunitions per round and was developed as a variant of the Army's M80 Dual-Purpose Improved Conventional Munition (DPICM) (Pike, 2005). In 2002, the navy decided to develop only a unitary warhead variant of the ERGM for two reasons. Tactically, the ERGM will mainly be used to attack hardened targets, such as bunkers, that would be better destroyed by a unitary warhead and to store the submunition warhead variant onboard ships would have required costly modifications to the ship's magazines (Keeter, 2002b).

The U.S. Navy's schedule for ERGM originally planned to take the munition into Initial Operational Capability (IOC) in 2001. However, after schedule delays, budget reductions, and developmental problems the IOC was moved to 2004 and later moved back to 2009 (Fein, 2006b). An independent assessment of the program by MIT Lincoln Labs in 2004 concluded that both the Navy and the contractor had underestimated the complexity of the technology (Erwin, 2005).

In June 2002, Naval Sea Systems Command team test fired seven ERGM rounds at pressure launch at Yuma Proving Grounds (YPG) in Arizona. Four of the projectiles had rocket motors, while three of them where dummy rounds that were equipped with a new tail fin assembly. These rounds were launched to evaluate airframe stability for the new tail fin assembly. All projectiles exhibited a stable flight path and landed where predicted. Two of the rounds' motors were conditioned to 110 degrees Fahrenheit (F) and two to 20^{o} F to test what effect extreme temperatures might have on the ignition of the rocket motors. All four rounds functioned perfectly (*ERGM Program Tests Rocket Motor, Aerodynamic Structures*, 2002; *ERGM Rocket Motor, Airframe Tests Successful*, 2002).

Another ERGM round was test fired on June 25, 2002, at the White Sands Missile Range (WSMR), New Mexico and flew 72 km (39 nm) in less than four minutes and performed better that the navy's tactical requirements of a 20 m Circular Error Probability (CEP) (Coskren, Easterly, & Polutchko, 2005). This test completed subsystem and system level design of the ERGM guidance, control, and propulsion systems and proved the electrical problems that had previously plagued the round had been fixed in that the electronic package were able to withstand the massive G-force of being launched out of the naval gun (*ERGM Completes Second Flight*, 2001). Hardening the electronics package had been one of the largest technical difficulties the program had faced. This test shot demonstrated that the electronics had been hardened enough to with stand 18 megajoules (MJ) of propellant, up from 12 MJ used in previous tests.

Though the ERGM round has had several good test firings, there have also been problems. Twelve years and $2 billion into the ERGM project, the navy is unsatisfied with the results and the number of set backs the projectile has faced (Erwin, 2005). Problems include, but are not limited to, power system failures, a software glitch causing the ERGM round to be unable to acquire GPS, failure to deploy tail fins upon exiting the gun barrel, failure to deploy steering canards in flight, and an underpowered rocket motor not capable of providing the required boost energy (Fein, 2005g).

Raytheon has been able to correct each developmental problem encountered: a software upgrade allowing the round to acquire GPS fixes in flight was developed, the fin and canard deployment problem was corrected, and a new high-energy Ex 99 nitramine propelling charge has been specifically developed by ATK (Ripley, 2003). Slow but steady progress has occurred throughout the development effort.

While Navy officials acknowledge the development effort of the munition has been disappointing, they insist that fleet commanders and the marines need this weapon and that the project must continue. At current expenditure rates, it is estimated that each ERGM projectile will carry a price tag greater than $50,000.

Despite all of this, the ERGM projectile has entered the second phase of testing. In this phase, the improved rounds will attempt to successfully duplicate the phase I tests. Once the phase II objectives are met, Raytheon is expected to build 20 to 40 projectiles and test them for phase III and develop a statistical database.

In 2009, Raytheon plans to conduct Developmental Testing and Operational Testing of ERGM at sea. The official said Raytheon will likely test upward of 60 to 80 rounds before the Navy undertakes a Milestone C decision. Initial Operational Capability (IOC) is planned for 2011 (Fein, 2005e; Fein, 2006a).

2. Ballistic Trajectory Extended-Range Munition (BTERM)

Confronted with the high estimated per-round cost of the ERGM, the Navy issued a broad agency announcement (BAA) for the development of alternative precision guided munition concepts to the EX-171 ERGM in October of 2003. The Navy stated it would like the projectile to cost $35,000 or less per unit with a unit cost objective of $15,000 (Cortes, 2003b). In response, ATK submitted the Autonomous Naval Support Round (ANSR) to the Navy.

ATK started ANSR as a self-funded initiative in the fall of 2000, pursued the program with Lockheed Martin (LM), Custom Analytical Engineering Systems (CAES), and Charles Stark Draper Laboratory (CS-DL). The round was developed under the Office of Naval Research (ONR) sponsorship in a government-small business partnership between the Naval Surface Warfare Center Dahlgren Division (NSWC-DD) and CAES CS-DL developed the guidance electronics and navigation system (Hunter, 2002a; Pike, 2006c). CAES designed the propulsion design, airframe, and control actuation (Hunter, 2002a). Allegany Ballistics Laboratory (ABL) is responsible for the ANSR system integration and the solid rocket motors. ONR has supported the development of ANSR and believed the projectile might serve as a complementary program to the ERGM and LRLAP.

ANSR's warhead was derived from the warhead found in the High-speed Anti-Radiation Missile (HARM). The entire munition weighed approximately 25 pounds, included ten pounds of explosive, and was fitted in a tungsten case that fragments upon detonation with the intent of showering the target area with metallic fragments (Pike, 2006c)

In January 2002, an ANSR projectile was successfully fired out of a standard Navy 5-inch/54 caliber gun to a range of 95 km (51 nm). Then in September 2003, two ANSR rounds were successfully fired at White Sands Missile Range and flew more that 113 km (61 nm), used input from nine GPS satellites, and landed within 20 meters of their intended targets (Cortes, 2003b). Based on these results, the Navy's objectives for an alternative precision guided munition were fully satisfied and in May 2004, the Navy awarded ATK the $29.9 million ERGM alternative demonstration contract (Fein, 2005e). The program to develop this round was renamed the BTERM.

BTERM, illustrated in Figure 4, was developed using commercially available components and a minimum of moving parts, following a purely ballistic flight trajectory to reach its target. This gives the BTERM projectile several advantages: it can get to its target in less time; it uses less airspace to get to the target, thus decreasing airspace deconfliction issues; and requires fewer in-flight adjustments. The BTERM's flight path is illustrated in Figure 5. In September 2003, a BTERM projectile successfully flew 100 km (54 nm) in a flight test. However, the BTERM has also had its own development problems. In June 2005, a BTERM projectile failed to reach its range objective in a test flight and although it flew over 79 km (43 nm), it did not reach the target. Then in October 2005, an unguided BTERM suffered a rocket engine failure (Fein, 2005e).

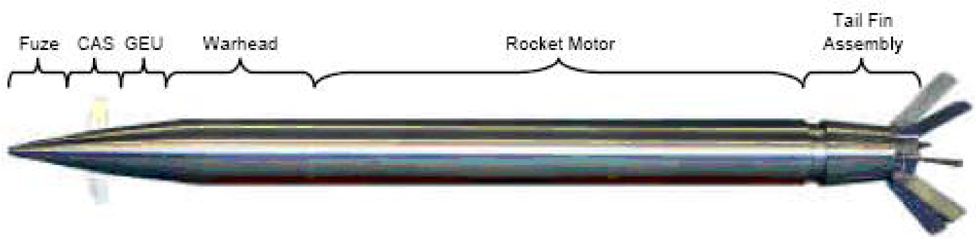

Figure 4. Diagram of BTERM components. Note that the BTERM only has two forward steering canards and six tail fins (From *Ballistic Trajectory Extended Range Munition (BTERM)*, 2004).

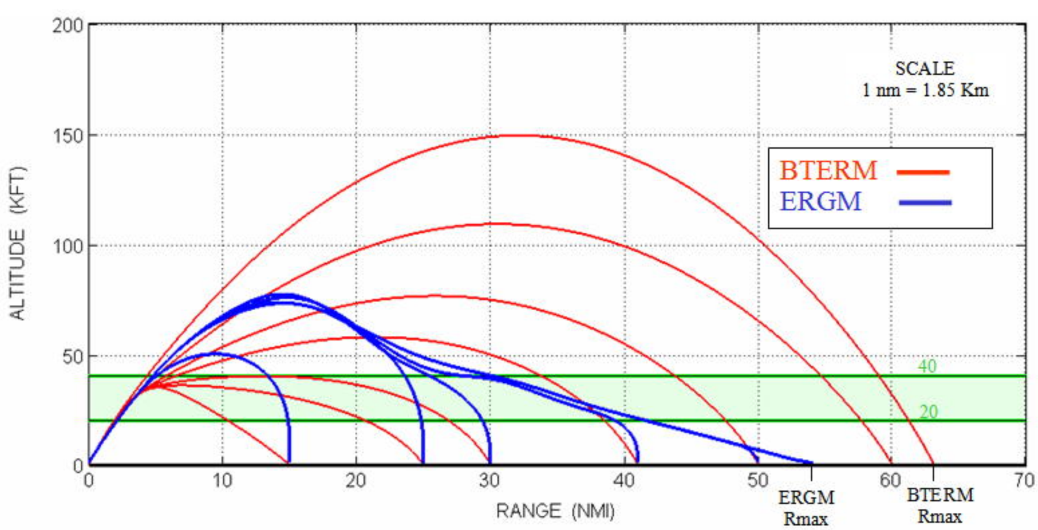

Figure 5. BTERM and ERGM Range and Ballistic Flight Profile. Note: Altitude is in kilofeet and range is in nautical miles (From Marsh, 2005).

In September 2005, ATK fired three rounds in order to perform an instrumentation checkout, a rocket motor qualification, and a guided flight test. After what was believed by ATK to be a successful test flight, ATK was confident that the project was back on track having "demonstrated full system capability" (Fein, 2005a). After the flight, ATK believed that the guidance and navigation control performed flawlessly and although the round needed some fine-tuning, they believed the round was on track for success (Fein, 2005a).

One week after ATK's test flight, the Navy indicated that it was not satisfied with the results of the BTERM's test flight. According to Program Executive Office, Integrated Weapons Systems (PEO IWS), the objectives of the September test flight included a demonstration of a range of 107 km (58 nm), a high terminal angle, 32 km (20 mile) guidance accuracy, control section performance, and an improved fin locking system. According to PEO IWS, "This was the second attempt to achieve guided flight … [while] some critical subsystems appear to have performed as required, once again the overall performance was not adequate." The guided flight round did not meet the objective of demonstrating accurate guided flight to the required range. The tailfin locking system functioned as required. The guidance system appeared to function, but further analysis is required to determine whether performance attributes were satisfactory" (Fein, 2005d). It is too early to identify the cause of the latest problem, according to the Navy and "a Failure Review Board has been established and is already working to identify the issue and implement a technical solution" (Fein, 2005d). After unsuccessful test flights in 2005 from both the ERGM and BTERM, there have been rumors that the Navy might consider terminating both programs and the Navy intends to issue a Request for Proposal (RFP). PEO IWS stated that "the Navy still plans to release an RFP in the near future for the ERM program and schedule modifications are being discussed" (Fein, 2005d).

Another issue facing ATK and Raytheon is that due to the importance of these programs to the Warfighter, there is the possibility that the ERM program might become an Acquisition Category (ACAT) I program. ACAT I programs are those that have been determined by the Secretary of Defense to be major defense acquisition programs (Fein, 2005d). In the fiscal year 2006 defense bill, ATK received slightly more than $10 million for continued testing of BTERM (Fein, 2006c).

In February 2006, ATK successfully conducted a short-range, guided flight test of the BTERM where the unboosted projectile flew more than 13 km (7 nm) and landed within two meters of the target (*5"/62 MK 45 MOD 4*, 2006). The flight test achieved all test objectives including high gravity gun launch survivability, muzzle exit conditions, guidance accuracy, and terminal angle of attack criteria (*ATK Conducts Successful BTERM Short-Range Engineering Test*, 2006). In April 2006, two unguided BTERM test firings achieved rocket booster ignition and performed complete burns validating the rocket motor and Ignition Safety Device (ISD) design. The ISD is critical to the round’s range performance across the entire set of range requirements, which extends from 28 km (15 nm) to 102 km (55 nm) (*5"/62 MK 45 MOD*, 2006).

3. Long Range Land Attack Projectile (LRLAP)

LRLAP is being developed as another low-cost round and was originally estimated to cost $35,000 per projectile (Kime, 2004). The LRLAP differs from the ERGM and BTERM in that it will be fired from the AGS and its funding is directly tied to both the AGS and DD-1000 with the project’s total $850 million dollar budget (Kime, 2004).

The LRLAP flight sequence is similar to that of the ERGM (see Figure 5), however, once the round reaches apogee, it has a greater ability to maneuver and fly to its target. An artist’s rendition of the LRLAP is illustrated in Figure 6. The LRLAP is 2 m (84 in) long, weighs approximately 113 kg (250 lbs), and is almost double the size of the ERGM and BTERM, which are both 5-inch projectiles. Like both the 5-inch ERMs, United Defense Industry (UDI) originally envisioned a family of munitions including LRLAP projectiles for unitary, high explosive, and submunition dispensing payloads, but like the ERGM and BTERM, the munition is being developed solely as a unitary warhead (Hunter, 2001; Hunter, 2002c). It is also planned that the delivered LRLAP be packaged for twenty years of storage life (Hunter, 2003).

Figure 6. An artist rendition of a LRLAP munition. Note that the LRLAP has four forward steering canards and eight tail fins (From *155 mm (LRLAP)*, 2004).

The U.S. Navy awarded UDI the contract for the AGS in 2000 and in an effort to reduce risk, subcontracted the LRLAP development to two competing teams: Raytheon Missile Systems (RMS) and Science Applications International Corporation (SAIC) teamed with Lockheed Martin (LM) (Hunter, 2002b). Both groups were provided a matching $20.3 million contract to develop a LRLAP. UDI selected LM/SAIC team over Raytheon on 1 April 2003 to complete the building of the LRLAP and the contract is valued at $40 million (Burgess, 2005). In developing the LRLAP, LM subcontracted CAES to develop the propulsion system, tail kit assembly, and most of the aerodynamic structure of the projectile, while the rocket booster is being developed by ATK. LRLAP will provide accurate fire support missions out to 154 km (83 nm) (Burgess, 2005). Although LRLAP is built by LM, it "draws on technology initiatives from the ERGM and the Army's Excalibur programs" and the "commonality among the three projectiles may reduce technical risk and cost" (Fein, 2005d).

Unlike its efforts with ERGM and BTERM, the Navy has seen successful results with LRLAP tests. The first ERGM, EX 171 MOD 0, test flights took place in February and December of 2001. During its flight, the ERGM met its engineering requirement for success with the GPS / INS system achieving an accuracy of least 10-20 m (30-60 ft) CEP at maximum range (Parsch, 2003).

During the most recent tests in the summer, the projectile impacted the predicted target area at ranges of 86, 109, and 117 Km (46.5, 59, and 63 nm) respectively, setting a distance record for gun-launched munitions which was previously held by the German Paris Gun (Burgess, 2005). These test flights demonstrated that the airframe, rocket motor components, fin stabilizing assembly, obturator (which holds the gas behind the projectile until it leaves the muzzle), steering canards, and GPS guidance system all performed up to specifications (Fein, 2005b).

In June 2004, LRLAP reached a new altitude of 27.4 km (90,000 ft) and covered 86 km (46.5 nm). Then on 28 July 2005, the Navy and the DD-1000 National Team conducted its fifth successful test of LRLAP fired from AGS. The projectile flew 117 km (63 nm) and met every range requirement (Fein, 2005c). According to the program director for DD-1000 at BAE, the success of these test flights “demonstrated that the DD-1000 National Team is on track to provide the U.S. Marine Corps fire-support capability for timely engagements over the horizon with highly accurate and lethal precision-guided projectiles" (Fein, 2005b).

Thus far, the LRLAP has met all the programs milestones and has completed integration and firing tests with the guided flight test demonstrating the LRLAP's ability to use an IMU with in-flight updates from a GPS to extend range while simultaneously achieving precision-strike lethality.

In July 2005, BAE Systems, a combination of British Aerospace (BAe) and Marconi Electronic Systems (MES), purchased UDI and awarded LM a $120 million contract for further development and testing of LRLAP. This cost-plus-award-fee contract covers additional development and tests during 2006-2008 and support to AGS qualification testing during 2009-2010. More than 100 projectiles are planned to be delivered and tested under this contract. Full-rate production is expected to begin in 2011 (*155 mm/62 AGS*, 2006).

G. RELATED EQUIPMENT

1. MK 45 Mod 4, 5-inch/62 Caliber Naval Gun

In order to accommodate the higher firing energies produced by the ERMs, the U.S. Navy contracted BAE to build the MK 45 Mod 4, 5-inch/62 caliber gun. BAE produced three Mk 45 Mod 4 models for development and testing. The first two guns were installed and successfully tested in July 1997 and August 1998 at the NSWC-DD. The third gun was delivered to Bath Iron Works (BIW) shipyard in June 1999 and installed in the USS Winston Churchill (DDG-81), as shown in Figure 7, in November 1999. Four additional gun mounts were installed in DDGs 82-85. In early 2002, the Mod 4 gun underwent additional developmental testing onboard the USS Lassen (DDG 82) using conventional ammunition where the gun successfully fired 457 conventional rounds. The first ERGM was successfully fired from the Mod 4 GWS on June 25, 2002, at WSMR (*Navy Weapons*, 2003).

Figure 7. Mark 45 Mod 4 on USS Winston Churchill (DDG-81) (From *5"/62 MK 45 MOD 4*, 2006)

The Mod 4 gun incorporates several improvements over the previous gun. The Mod 4 allows the operating service chamber pressure to increase from 55,000 to 65,000 psi (*Navy Weapons*, 2003). When fired (see Figure 8), the conventional 5-inch round produces approximately 10 MJs of energy, while ERMs produce around 18 MJs due to their high-energy propellant. In addition to firing ERGM rounds, the Mk 45 Mod 4 gun will retain the capability to load and fire the current inventory of conventional 5-inch ballistic ammunition (*5"/62 MK 45 MOD 4*, 2006). The gun's analog control system has also been replaced with a digital control system, allowing the gun weapon system to interface better with the Mk 60 Gun Computer System and to integrate with equipment, computer programs, operator stations, and other newly installed weapons systems.

Figure 8. The MK 45 Mod 4 test firing a conventional round (From Annati, 2003).

Modifications to the new gun include a lengthened 62-caliber barrel, strengthened gun chamber and trunion supports, lengthened recoil stroke, an interactive touch-screen control system, and a new gun mount shield to improve maintainability and reduce overall radar signature (Fein, 2006b). Other modifications include an Ammunition Recognition System (ARS), a Gun/ERGM interface and improvements in the ammunition magazine to facilitate stowage of the larger ERGM rounds and assist shipboard ammunition handling and gun loading (*5"/62 MK 45 MOD 4*, 2006). The ARS can identify ERGM projectiles and propelling charges and preclude the unsafe mixing of ERGM and conventional ammunition. The gun/ERGM interface allows the ERGM rounds to interface with the MK 160 Gun Computer System to load pre-flight data into the guidance and navigation subsystems of the projectile prior to loading and firing.

The Mod 4 gun is expected to be installed in Arleigh Burke-class Aegis destroyers (DDGs 81-108) and in Ticonderoga-glass Aegis cruisers (CGs 52-73) as part as part of the Cruiser Modernization program although these gun models are designed to only shoot the conventional 5-inch munition and not ERMs (*5"/62 MK 45 MOD*, 2006).

2. Advanced Gun System (AGS)

UDI began developing the AGS, illustrated in Figure 9, in 1999 for the DD-21 Zumwalt Class land attack destroyer. However, when the second Bush administration canceled the DD-21 program, the AGS was slated for fitting on DDG-1000. UDI has been awarded a $300 million contract through fiscal year 2005 to design the AGS for the DD-1000. AGS draws from the experience of two other United Defense projects: the Crusader 155 mm howitzer and MK 45 Mod 4 Naval Gun. In October 2001, the first prototype of the AGS was successfully proof-tested, firing eleven test projectiles. AGS qualification tests are to take place in 2009 and future production is expected when the first DDG-1000 becomes operational in 2012. Each gun's magazine holds 750 rounds and an AGS firing LRLAP at 12 rounds per minute was considered equivalent to one 155 mm artillery battery (six guns) firing at a rate of two rounds per gun per minute (*155 mm/62 (6.1") AGS*, 2006).

Figure 9. An artist's rendition of the AGS firing a LRLAP (From 155 mm (AGS), 2005).

The AGS was formerly known as the Vertical Gun for Advanced Ships (VGAS), because it was originally designed as “twin cell” vertical loading gun in order to meet the requirement of firing 12 rounds per minute. However, a June 2004 program review conducted by the CNO decided to use the vertical load design and reduce the firing rate requirement to 10 rounds per minute. This review also decided to equip each DDG-1000 with two AGS mounts. According to the DDG-1000 program managers, the CNO’s decision was influenced by several other ship-wide benefits that this change provided. The vertical load design reduced the weight of the gun from 215,000 to 130,000 lbs, reduced the deck penetration from 17 to 11 ft, and increased the structural strength of the DDG-1000 (Cortes, 2003a). The twin-cell cradle also had more moving parts than vertical load and is therefore expected to be less expensive to build, less prone to break, and easier to maintain. According to UDI’s program director for DD-1000 programs, the vertical load configuration does not affect the LRLAP round's performance or design (*United Defense awarded $376 Million for ongoing AGS work*, 2005). With the more traditional vertical-load design, both conventional as well as guided munitions may now be used making the concept of this weapon similar to that of the Mark 45 Mod 4 5-inch/64 caliber program. However, ballistic round development for AGS is not funded and existing US Army or NATO 155 mm projectiles cannot be used in AGS (*155 mm/62 AGS*, 2006).

With the wars in Iraq and Afghanistan, the future of the DDG-1000’s acquisition plans are uncertain, however, the Navy continues to award contracts for its future destroyer. In June of 2005, the UDI was awarded an additional $376 million for continued development and testing of the AGS and LRLAP. UDI was purchased by BAE Systems in March of 2005 (*BAE Systems*, 2006). The program director for the DD-1000 program at UDI, Armament Systems Division believes "this contract award recognizes the importance of the Advanced Gun System and its LRLAP ammunition to the Navy to perform long- range fires in support of the Marines in future land attack scenarios" (*United Defense Awarded $376 Million for ongoing AGS work*, 2005). The AGS is scheduled to be delivered to the fleet in September 2010 (*United Defense awarded $376 Million for ongoing AGS work*, 2005).

Recently, another platform has been considered for the AGS: the San Antonio-class (LPD-17) amphibious ship. The San Antonio class is a Landing Platform Dock (LPD) ship that is being built with space for a Vertical Launch System (VLS) in its forward structure that can be replaced by the AGS (*5"/62 MK 45 MOD 4*, 2006).

Arming amphibious ships with guns is not new to the Navy. The USS Tarawa Class (LHA - general-purpose amphibious assault ships) were originally equipped with two 5-inch 54 caliber guns as illustrated in Figure 10, however these guns were removed in the early 1990's.

Figure 10. USS Peleliu (LHA 5) circa 1980. Note the two MK 45 Guns mounted on either side of the forward flight deck (From *USS Peleliu (LHA 5)*, n.d.).

3. DDG-1000 (formerly DDX)

In the 1990s, U.S. Navy planners developed operational requirements for the next generation of surface combatants. These requirements were based on future threats envisioned in the littoral operating environment and led the navy to create the next-generation destroyer DD-21. In Phase I of the development, the navy contracted two teams to build the DD-21: the Blue Team, led by BIW with LM as the systems integrator, and the Gold Team, led by Ingalls Shipbuilding Inc. with Raytheon as the systems integrator (*DDG-1000*, 2006). The intent was to choose the most cost effective program prior to entering Phase II. However, on 31 May 2001, the Under Secretary of the Navy suspended the DD-21 Program pending completion of a Shipbuilding Study, the Quadrennial Defense Review, and the Secretary of Defense's Strategic Review (*DDG-1000*, 2006).

Figure 11. An artist's rendition of the DD-1000. Note that the AGS is in the stored position (From *DD(X) Composite Images*, 2006).

In November 2001, the DD-21 program was resurrected as the DD-1000 program and the contract was awarded to the team led by Northrop Grumman (NG) in April 2002. During Phase III, the DD-1000 National Team, led by NG Ship Systems who serving as the lead role in system design, engineering prototype development, and testing and Raytheon as mission systems integrator, will continued development and design of the DD-1000 (Cortes, 2003a). Overall, the DD-1000 National Team involves more than thirty engineering and maritime industrial companies in almost every state working with the navy on the program. In order to support the vitality of the ship building industry, the navy has proposed dual-yard acquisition strategy where NG and BIW will both simultaneously build DDG-1000 beginning in fiscal year 2007 with a $2.6 billion budget (Pike, 2006a). The U.S. Navy believes the "dual lead ship" strategy will maximize the competitive pressure between the shipyards keeping the design efforts on track and reducing costs.

Under the $3 billion DDG-1000 Detail Design and Integration contract awarded by the Navy in May 2005, Raytheon continues its long-standing role as the prime mission systems integrator for DDG-1000 (*DD-1000 Program*, n.d.) the navy’s current estimate is $3.3 billion for each lead ship while follow ship costs are projected to be significantly less. Based on the current build profile, the cost estimate for the fifth ship is $2.3 billion (*DDG-1000*, 2006).

In April 2006, the Navy announced that the first DD-1000 destroyer will be designated DDG-1000 and the lead ship in the class will also be named in honor of former CNO Admiral Elmo R. Zumwalt, Jr. (Pike, 2006b). Developed under the DD-1000 destroyer program, DDG-1000 Zumwalt is the lead ship in a class of next-generation, multi-mission surface combatants. The DD-1000 is the centerpiece of a surface combatant family of ships that will deliver a broad range of capabilities and provides the baseline for spiral development of technology and engineering to support a range of future ship classes such as CG(X), LHA(R) and CVN-21 (*DDG-1000*, 2006).

DDG-1000's armaments package includes two AGS, an eighty cell Advanced Vertical Launch System (AVLS), two 40 mm guns for small boat defense, and an anti-submarine warfare suite (Marsh, 2005). It is estimated that a single DDG-1000 armed with two AGS will be able to deliver a firepower equivalent to a battery of six 155 mm field guns, with an increased range, precision, and lethality, and without the need to move around the battlefield guns, vehicles, ammunition, and crews. Each gun will have a 300-round magazine with an additional 320-round auxiliary magazine.

The DDG-1000 will also be equipped with a fire suppression system, automatic damage control systems, Integrated Power System (IPS), electric propulsion system, and a SPY-3 Multi-Function Volume Search Radar (MFVSR) (*U.S. Navy Building Site to test Electric Rail Gun*, 2004). Structurally, the ship is designed with a 'wave-piercing’ hull and a 50-fold smaller radar cross section compared to current destroyers.

The DDG-1000's IPS will be an all-electric drive consisting of four prime movers (electrical driven engines) that will provide power to all the ship's systems and eliminate the need for a driveshaft and reduction gears. This in turn will greatly reduce the acoustic signature of the ship. The IPS will also provide ten times more available power than conventional ships and will provide the power necessary for future electromagnetic based weaponry (*Navy of the Future DD(X)*, n.d.).

The Peripheral Vertical Launch System (PVLS) clusters missile magazines (four missiles per launchers) between the layers of the inner and outer steel of the ship. This provides the DDG-1000 a great ability to continue fighting if one of the missile magazines mass casualty and if one is struck, the resulting explosion will vent away from the ship. The PVLS will be able to launch several types of missiles: tomahawk land attack missiles, standard missiles for local air defense, Sea Sparrow missiles, and antisubmarine rockets (*Navy of the Future DD(X)*, n.d.).

The Navy's fiscal year (FY) 2006-2011 Future Years Defense Plan identified funding for one ship per year from FY 2007 to 2011 for a total of 5 ships as of December 2005, and the Navy plans to build 8 to 12 DDG-1000s overall. The Marine Requirements Oversight Council believes there is a need for twenty-four DDG-1000s in the fleet to fully support a major combat operation and that this mission cannot be fully supported with less than twenty-four ships (Pike, 2006b).

4. Electromagnetic Rail Gun (EMRG)

In 2004, the navy broke ground at the NSWC-DD, Dahlgren, VA, to build a test site for the electromagnetic rail gun (EMRG) (U.*S. Navy Building Site to test Electric Rail Gun*, 2004). According to the Sea Strike concept of Sea Power 21, future naval forces will employ rail gun technology. The CNO's SSG XVI concluded that rail gun technology offers the most promising option for providing cost effective long-range NGFS (Adams, 2003).

The EMRG has been a long-term project for the ONR and they have budgeted about $220 million over the Future Years Defense Budget to fund its research (Roosevelt, 2005). In October 2005, ONR awarded BAE, General Atomics, and NG $1.5 million contracts each to develop a 12 m, light-weight gun barrel for the navy's proposed electromagnetic rail gun (Fein, 2005f). It is believed that the ERGM could deliver an unguided projectile with an impact velocity of Mach 5 to targets at ranges of 250 miles at a rate of greater than six rounds per minute. ONR believes that a full-scale demonstration is feasible around 2014 and the weapon could see service in the fleet by 2019.

The EMRG's munitions have several advantages over the current ERMs in that these projectiles will be smaller, have greater range, and will not require propellants or explosive warheads. Conventional or non-rocket boosted naval gunfire is limited, due to the physics of gas expansion, to a muzzle velocity of about 1.5 km/s. This limited-muzzle velocity constrains the range of the projectile to less than 50 miles. Using a rocket boost can increase this range to 100-plus miles, but weight restrictions cause a trade off between rocket fuel weight, warhead weight, and range. Because an EMRG's munition does not use a propellant, it is easier to store and increases the ship's capability to carry more rounds. It is estimated a rail gun magazine might hold as many as 10,000 rounds using the same 600-round magazine capacity of the AGS (Adams, 2003).

The rail gun's ability to reach an extremely high muzzle velocity is the key to its cost effective increase in range and lethality (Adams, 2003). The other benefit of the ERGM is that its projectiles are kinetic weapons, in that they get their destructive power by converting their kinetic energy into force. The current 5-inch 54 caliber has the muzzle energy of 10 MJ, the 5-inch 64 caliber will have 18 MJ, the AGS is believed to be able to achieve 33 MJ, and the ERGM is estimated to be able to achieve 60 to 300 MJ (Adams, 2003). One test demonstration of the EMRG's projectiles kinetic energy release upon impact created a crater 3 m (10 ft) diameter by 3 m (10 ft) deep in solid ground. The projectile can also penetrate material up to 12 m (40 ft). This type of destructive power is capable of destroying most hardened targets with one round (Adams, 2003). An ERGM is uniquely suited for deep strike, interdiction, and combat air support. In the eight hours of combat, one ERGM can deliver twice the payload, three times the energy, and hit ten times as many targets as an air wing of F/A-18s (Adams, 2003).

Developing the ERGM is not without its challenges. It is unknown how accurate an unguided round would be and it will be extremely difficult to develop a guidance package to withstand the 45 MJ forces the firing causes (Fein, 2005f). However, efforts toward this have been achieved with the ERGM/LRLAP rounds which have the capability to survive a 12 MJ launch. The ERGM requires large amounts of electricity to provide the instant electrical charges required to be fired. To support the ERGM, the navy is building the DDG-1000 with an electric propulsion system.

H. SUMMARY

This section presents work related to naval gunfire and the ERMs and related equipment that are currently being developed and how naval gunfire has been employed through out history including the influence that modeling ballistics projects simulated and influenced the development of the first super computers.

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III. ENVIRONMENTAL EFFECTS ON MUNITIONS

A. INTRODUCTION

This chapter outlines methods of gathering environmental data for use in ballistics, the history and fundamentals of numerical weather prediction, including a review of the U.S. Military's NWP centers and NWP models currently in use, and previous studies of environmental effects on ballistics.

B. TYPES OF ENVIRONMENTAL DATA USED IN BALLISTICS

1. Direct Observations Radiosonde

A radiosonde is a balloon-born meteorological tool capable of directly sampling the atmospheric column for the surface to approximately 30,000 m (100,000 feet or 10 mb). The main component of the radiosonde is a lightweight instrument package illustrated in Figure 12. The radiosonde is attached by a string to a balloon. The instrument has a temperature sensor, humidity sensor, and an aneroid barometer and contains a small FM radio transmitter that transmits the collected information to a receiving station. Their equipment is powered by a small battery which is activated by immersing it in water prior to launch.

Figure 12. Radiosonde instrament package (From *Radiosone*, 2006).

The radiosonde is carried into the atmosphere by a balloon filled with either helium or hydrogen. Once the balloon is launched, it ascends and expands in size from approximately 2 m (6 ft) in diameter to 10 m (32 ft) in diameter before it bursts. Newer radiosondes have an attached parachute that will safely return them to the ground once the balloon bursts and contain mailing instructions they can be returned and refurbished (*NWS Radiosonde Observations – Fact Sheet,* 2001). However, balloons can also be fitted with a small leak preventing them from bursting. This method allows the balloons to gather environmental data on ascent and decent. Typically, these 'rigged' radiosondes do not reach their maximum height potential.

Radiosondes measure wind speed and direction using Loran C or GPS. Observations where winds aloft are also obtained are called "rawinsonde" observations and the term 'rawinsonde' is often used interchangeably with radiosonde. They also measure pressure, altitude, position (latitude/longitude), temperature, and relative humidity. Typically radiosonde data is used to construct a Skew-T log-P diagram shown in Figure 2. Radiosonde data are an important data component of NWP. Radiosonde data are often used as a vertical profile of the atmosphere, however, as the instrument ascends, it moved by winds. Figure 13 shows the Skew-T diagram plot produced from the data of a radiosonde launch, while Figure 14 shows latitude and longitude drift of this launch. Because a radiosonde may drift several hundred kilometers during their flight, this can introduce accuracy problems into the analysis as they do not provide a truly vertical profile of the atmosphere. Radiosondes also take up to two hours to reach their max altitude and the data they provide is often time late (*NWS Radiosonde Observations – Fact Sheet,* 2001). Thus a variety of error factors pertain.

Radiosonde data is often used for naval gunfire and artillery shooting. When this type of environmental data is used, it is considered to represent a vertical profile of the atmosphere at the launch point. However, Figure 14 shows that as the radiosonde ascends, it is moved about by the same wind that it is measuring. Thus, this data source does not provide an accurate vertical fixed-time profile of the atmosphere. Another weakness in using this data for gun shoots is that is does and can not provide environmental data at the firing unit, at target, or along the trajectory between the two.

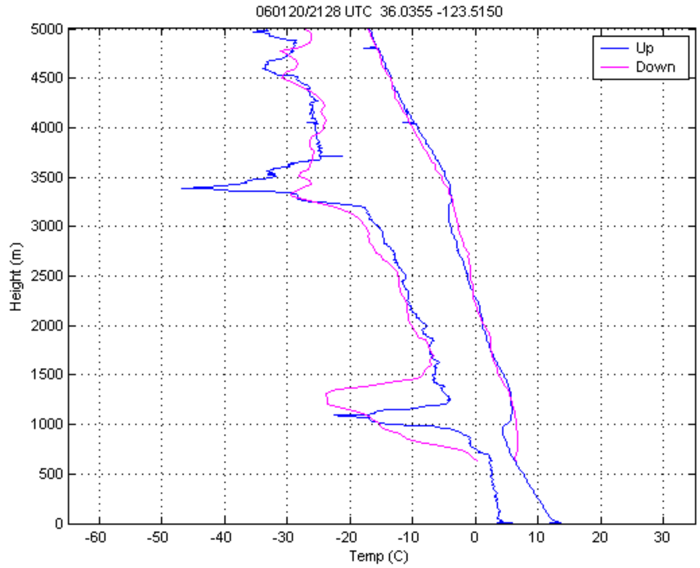

Figure 13. Skew-T diagram created from a 'rigged' radiosonde launch. This radiosonde gathered atmospheric data on it as ascent (blue line) and descent (red line). As shown the plot, the atmospheric values collected varied during the ascent and descent.

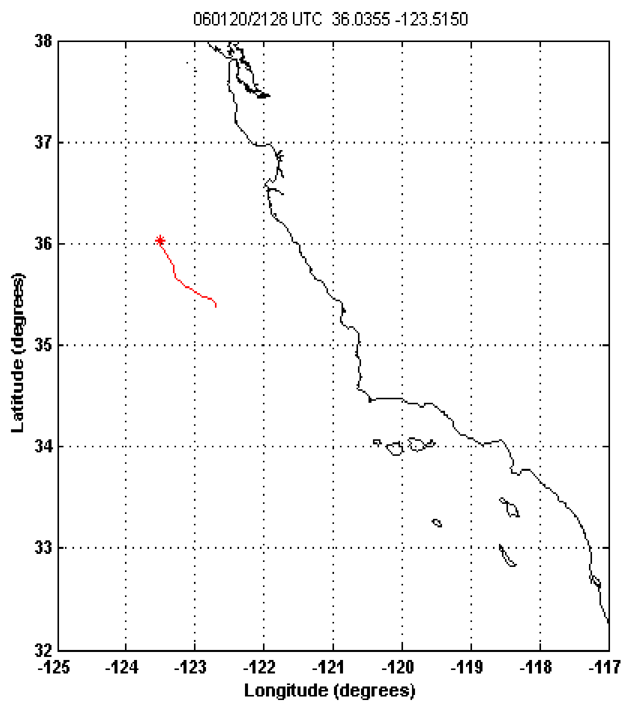

Figure 14. Corresponding radiosonde latitude and longitude drift plot constructed from the launch gathered data used in Figure 13. This radiosonde traveled approximately 170 km while collecting atmospheric data.

2. Numerical Weather Prediction (NWP)

NWP is the science of using high-performance computer modeling to forecast future weather using equation-based models of the atmosphere and computational techniques. The process of NWP is covered later in this chapter. It has been suggested that NWP output is the best suited for use in ballistics as it has the ability to provide forecasted weather data over a large 3-dimensional (3D) area that is not time late.

C. HISTORY OF NUMERICAL WEATHER PREDICTION (NWP)

1. Origins of NWP

Vilhelm Bjerknes first recognized that NWP was possible in principle in 1904 and proposed that weather prediction might be seen as essentially an initial-value problem in physics and mathematics (Shuman, 1989; *NWP Equations*, 2006). He theorized that since equations govern how meteorological variables change with time, provided the initial condition of the atmosphere and these governing equations, they can be solved to obtain new values thus making a forecast.

Over ten years later, L. F. Richardson described in great detail the tasks required to collect and analyze the data required to produce a numerical forecast (Shuman, 1989). Richardson's basic problem was that the supporting computer technology was not available to gather, store, and compute the required amount of data to produce a workable forecast. However, the fundamental procedures proposed by Richardson resemble the ones used today in NWP.

2. Electronic Numerical Integrator and Computer (ENIAC)

The history of supercomputing, NWP, and calculating projectile ballistics started in 1943 with the first computer: the Electronic Numerical Integrator and Computer (ENIAC). The ENIAC is widely regarded as the first general-purpose electronic digital computer and was built to calculate ballistic tables for projectile trajectories.

The Ordnance Department of the Unites States Army conducted its weapon testing at the Aberdeen Proving Ground in Maryland. In order for the guns to reach their intended target, trajectory tables were calculated to illustrate how far a round could travel given the inclination of the gun and other considerations such as wind speed and direction, temperature, atmospheric pressure, humidity, and the projectile type. For each gun, several different tables were calculated to account for the varying conditions in which the gun would be used (Boyce, 1999). Computing the ballistic tables required three-dimensional, second-order differential equations of motion, which were calculated by hand taking roughly 20 hours per table entry (Boyce, 1999).

To produce ballistic tables, the United States Army contracted the Ballistic Research Laboratory (BRL). With the outbreak of World War II, BRL found itself greatly understaffed and as the war accelerated, the demand for more ballistic tables increased beyond what they were able to manage (Geselowitz, 2006). In order to provide the Army with the required number of ballistic tables, BRL invested in a Bush differential analyzer. The Bush differential analyzer was able to perform the same calculations as a modern day scientific calculator. By using the Bush differential analyzer, BRL was able to reduce the time to calculate a single ballistic table entry from 20 hours to 15 minutes. However, even with this improved calculation time, the BRL could not keep up with the number of tables that were required.

In searching for a faster way to compile these ballistic tables, the Army discovered that the Moore School of Electrical Engineering at the University of Pennsylvania also had a Bush differential analyzer and that their analyzer was capable of integrating up to fourteen units. The Army then contracted the Moore School to help BRL calculate ballistic tables. In order to better train future employees, BRL instituted a program of study at the Moore School to train students in various technical fields to assist in the war effort.

As mentioned earlier, the Bush differential analyzer, while able to perform calculations faster than a human, was still inefficient for the vast amounts of tables that the Army required. Scientists at BRL understood that a digital machine would be able to work faster than the Bush differential analyzer and could solve their problem. In 1943, they designed and began work on a new digital machine that would have considerable speed enhancements over that of the Bush differential analyzer. Two years later, in April of 1945, the machine was complete.

This machine was called the Electronic Numerical Integrator and Computer or ENIAC and proved to be the solution. In addition to calculating ballistic tables, the ENIAC's computing power was used for computing the multivariable calculation required for NWP. The first successful NWP forecast was run on the ENIAC in 1950. This was a simple Barotropic model that took 24 hrs to produce a 24 hr forecast (Shuman, 1989).

As mentioned earlier, Richardson first proposed the principle of numerical forecasting in 1922, but it was not until the late 1940s, with the invention of the ENIAC, that computers were powerful enough to run prediction programs developed by Charney, Fjortoft, and von Neumann (Edkins, 1987).

3. Institute for Advanced Study (IAS)

In 1946 John von Neumann organized the Electronic Computer Project at the Institute for Advanced Study (IAS) in Princeton, New Jersey (Shuman, 1989). The goal of the project was to design and build a more powerful computer and had three focus areas: weather forecasting, numerical mathematics, and engineering. In 1948, J. G. Charney established the Meteorology Group within the IAS with the goal to use this new computer to apply the dynamic laws of physics to weather forecasting. Once the IAS computer was completed, the same NWP model previous run on the ENIAC was run on the IAS computer and took less than 5 minutes to produce a forecast (Shuman, 1989).

4. Joint Numerical Weather Prediction Unit (JNWPU)

The Joint Numerical Weather Prediction Unit (JNWPU) was formed, staffed, and funded by the U.S. Weather Bureau, U.S. Air Force, and U.S. Navy in 1954. JNWPU purchased a general use IBM 701 for NWP and began to issue NWP forecasts twice a day. However, these forecasts had serious flaws and could not match those provided by professional meteorologists. However in 1958, a suitable automatic data handling and analysis system was invented. This new system provided the ability to analysis and process large amounts of data and led to the computational breakthrough allowing NWP forecasts to become ‘operational’ meaning the that the forecast were suitable to use in producing an accurate weather forecast.

Figure 15 shows the graphical improvement of S_1 score between 1955 and 1988. S_1 scores are developed from the accuracy of a 36 hr prediction of geopotential height at 500 mb. The S_1 score is a rough, but accepted, measure of the normalized room mean squared vector error of geopotential height gradient. The area of verification for this illustration of these S_1 scores covers North America and adjacent waters. In terms of practical skill, a S_1 score of 20 is perfect, while 70 is worthless. The formula used is skill percent = 2 x (70 – S_1) (Shuman, 1989).

By 1960, many NWP forecast products surpassed those made manually by the National Meteorological Center (NMC) and about 95% of them were produced automatically (Shuman, 1989).

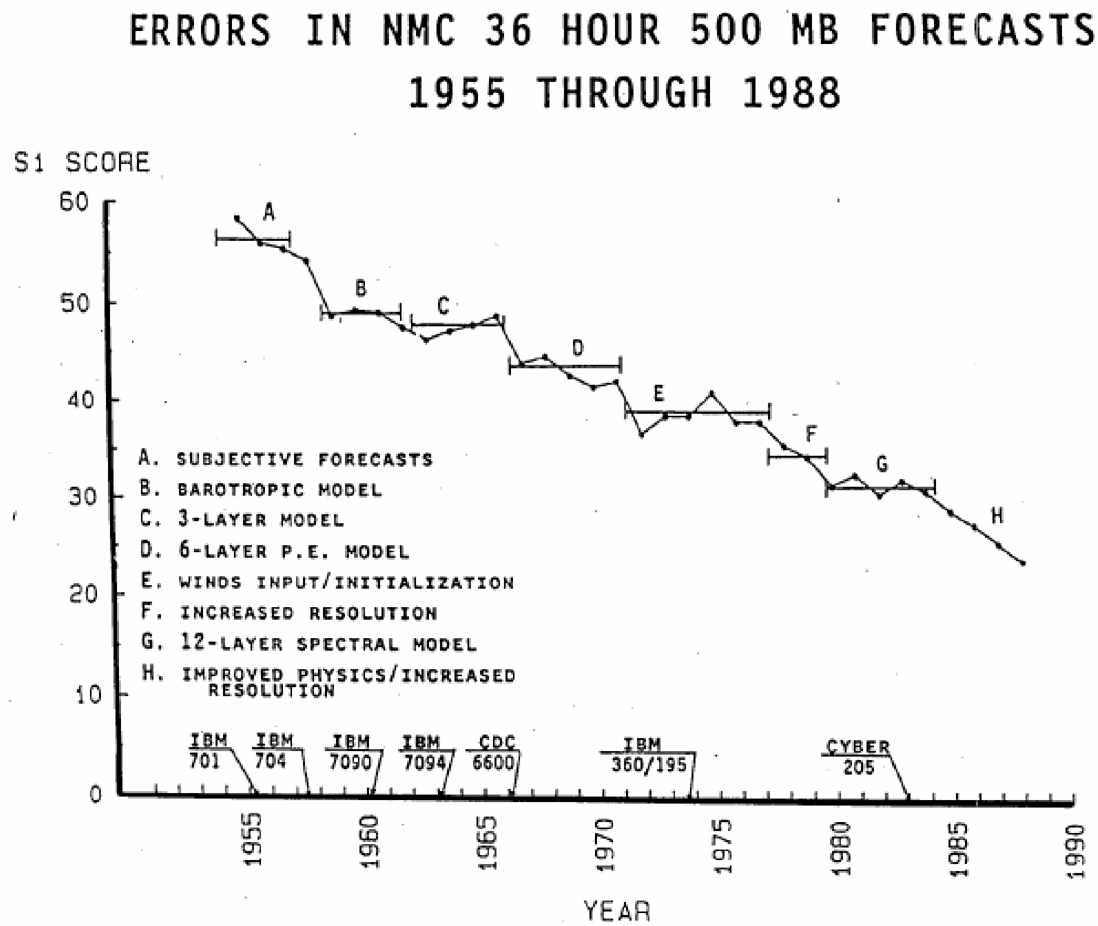

Figure 15. Record of S_1 scores for 36 hr predictions of geopotential height at 500 mb from 1955 to 1989 (From Shuman, 1989).

5. Meteor

The first computer developed and used solely for numerical weather prediction was purchased in 1962 by Met Office of the United Kingdom (UK) (*History of the MET Office,* n.d.). This computer, a Ferranti Mercury and nicknamed 'Meteor,' was operated by punched paper tape (Hinds, 1981).

The Meteor was able to run a two-level numerical model of the troposphere for the North-Eastern Atlantic and Europe on a 320 km grid, forecasting out 36 hours (Ratcliffe, 1993). The Meteor was able to process 3×10^3 cps and took several hours to run a forecast. Due to the experimental model runs and frequent breakdowns, the Meteor cannot be regarded an operational forecasting computer (Sumner, 1964).

6. Comet

By 1965, the Met Office's second computer, the English Electric/LEO KDF 9 - nicknamed 'Comet' was purchased. The Comet used a three-level troposphere quasi-geostrophic model with a horizontal resolution of approximately 300 km (Gadd, 1985; Miles, 1971). The Comet had an average operating speed of 5×10^4 cps and a memory 12 times the size of the Meteor (Hinds, 1981). The numerical model ran twice daily and was able to initially provided operational forecasts out to 30 hrs and experimental forecasts out to 72 hours (Ratcliffe, 1993).

7. CDC 6500

In 1967 FNMOC, then named Fleet Numerical Weather Center, purchased the first Cray CDC 6500 which had dual processors. Then in 1969, FNMOC purchased a second CDC 6500 (Rosmond, 2004). Using these computers, FNMOC produced the world's first multiprocessor production code using shared model data (Rosmond, 2004).

8. IBM 360

In 1972, the Met Office purchased the IBM 360/195, which has a speed of 4×10^6 cps and a main memory 20 times that of the Comet. The computer allowed a 10-level (each of 100 mb) primitive-equation model with a resolution of 300 km for the Northern Hemisphere (north of 15° N), 100 km resolution for a nested model of Europe and the North-Eastern Atlantic, and allowed the numerical model to be refined where needed, which increased forecast accuracy (Flood, 1985).

9. CDC Cyber 203/205

In 1976, FNMOC purchase a CDC Cyber 175, which was upgraded in 1980 to a Cyber 203, and two years later further upgraded to CDC Cyber 205 and the Met Office also purchased a CDC Cyber 205 (Rosmond, 2004; *History of the MET Office,* n.d.). This supercomputer operated at 2 x 10^8 cps and allowed a 15-level primitive-equation global model to run operationally for the first time. Global forecasts for up to 144 hours were routinely produced with a resolution of 150 km (1.5° latitude x 1.875° longitude) and nested limited-area model grid spacing resolution of 75 km (Gadd, 1985). Climate modeling also became a reality, using an 11-level global model with 260 km resolution (Rogers, 1988).

The Cyber 205 was approximately six times more powerful that its predecessor in both speed and capacity and 10,000 times more powerful than the IBM 701 (Shuman, 1989). Figure 15 illustrates the reduction of the S_1 score with the implementation of each new computer.

10. Cray C90 Series

The Cray Y-MP C90 was purchased in 1991 and for the first time was able to use multiple processors (*History of the MET Office, n.d.*). With 1 x 10^9 calculations per second (cps), it was possible to run a mesoscale (smaller) model at 17 km resolution within the new 19-level global model (Cullen, 1993). This global model ran 4 times a day and for the first time covered the entire height of the atmosphere with the increased resolution of 90 km.

In 1991, the Met Office purchased the Cray T3E-900 C90 (*History of the MET Office, n.d.*). The T3E was the first computer with the ability to use Massively Parallel Processor (MPP) architecture. Unlike IBM 360/195 which had a single processor or the Cray Y-MP which had several processors, the T3E used hundreds of relatively inexpensive 'off the shelf' processors. The production of the T3E basically ended the high-overhead cost required to upgrade to better supercomputers and introduced “cheap supercomputing” (Rosmond, 2006).

Using 696 processors (compared with the 16 processors in the C90 Y-MP), the Cray T3E C90 increased processing speed to 3 x 10^{11} cps (Galvin, n.d.). With recent upgrades, the T3E currently uses 856 processors and runs a 65-km global grid with 30 levels. The embedded mesoscale grid has 12 km resolution and 39 levels, covering the entire depth of the atmosphere and now produces four forecasts per day out to 36 hrs ahead over an area almost twice as large as that of its predecessor. The model run included 3D, high-resolution ocean models and various climate models running at a resolution of 130 km. The climate models ran on a duplicate machine that served as a stand-by computer if the first T3E failed.

11. Silicon Graphic, Inc (SGI) Origin 3000

In 2001, FNMOC replace the Cray C90 Series with the Silicon Graphics, Inc (SGI) Origin 3000 series supercomputer illustrated in Figure 16. The SGI O3000 currently runs 1,152 processors and uses a patented NUMAflex concept. NUMAflex system allows the computer system to independently scale the number of 'bricks' of processors working on a job which provides unprecedented levels of flexibility, resiliency, and investment protection. With this system the SGI O3000 bricks can be configured as a single 512-processor shared-memory system or can be split into as many as 32 partitions and run as a tightly coupled cluster with thousands of processors (*Fleet Numerical Meteorology and Oceanography Center*, 2002).

Figure 16. SGI O300 at FNMOC (From *Fleet Numerical Meteorology and Oceanography Center*, 2002)

FNMOC reached full operational capability in 2001 with four SGI O3000 series systems deployed: a 512-processor system, a 128-processor system handling all computeintensive modeling functions, and two 12-processor systems provide storage and data management functions. In aggregate, these systems provide 20 times the compute capacity of FNMOC's older Cray C90 series systems and an unprecedented ability to scale performance and other capabilities for the future. Each day, this system currently processes over 6 million observations and outputs over 5,000 oceanographic and atmospheric charts, analysis, forecasts, and related data sets (*Fleet Numerical Meteorology and Oceanography Center Selects SGI*, 2004; *Fleet Numerical Meteorology and Oceanography Center Selects SGI Supercomputers and Service for Global Weather Forecasting*, 2004).

D. NUMERICAL WEATHER MODELING CENTERS

1. Fleet Numerical Meteorological and Oceanographic Center (FNMOC)

FNMOC is the principal weather and ocean prediction center within the Department of Defense (DOD). FNMOC began as the Navy Numerical Weather Project (NANWEP) in 1958 in Suitland Maryland, and a year later moved to Monterey California, to share expertise and computer resources with meteorologists at the NPS (*Fleet Numerical Meteorological and Oceanographic Center (FNMOC), n.d.*).

FNMOC has a well-established and time-tested infrastructure for twenty-four hour computer systems support; observational data decoding and quality control; meteorological satellite data processing; data management; numerical weather and ocean model production run management; and product visualization, quality control and distribution. Building on these capabilities, FNMOC is particularly successful in its Numerical Weather Prediction (NWP) program that provides a broad range of products and services that support numerous customers worldwide. FNMOC is recognized internationally as one of the world's premier NWP centers.

FNMOC fulfills the military's requirement for an operational NWP capability that is operated in a secure, classified environment protected by DOD-certified network firewalls. This requirement is driven by the importance of weather on modern military operations, the need to utilize classified weather observations, and the ability to produce and distribute classified weather-related products.

Fleet Numerical also provides an important and physically separate backup for National Weather Service and thus its secondary role is a key component in the U.S. national program for weather prediction.

FNMOC operates at the leading edge of science and technology, and benefits greatly from collocation with its supporting research and development activities. These activities include the Naval Research Laboratory, Monterey Detachment (NRL/MRY) and the NPS. NRL/MRY is a world-class research organization that focuses on weather-related support for the warfighter. FNMOC and NRL/MRY are collocated, sharing office space, data, software, and computer systems. Together FNMOC and NRL/MRY represent one of the largest concentrations of weather-related intellectual capital in the nation. This collocation and cooperation between research and operations is the optimum arrangement for quickly transitioning research and development cost-effectively into new and improved operational weather prediction capabilities (*Fleet Numerical Meteorological and Oceanographic center (FNMOC), n.d.*).

FNMOC has close ties with NPS, particularly in the areas of meteorology, oceanography, information technology, and operations research. NPS serves as one of FNMOC's "think tanks" on emerging warfighting issues, bringing interdisciplinary talent to bear on these issues through research, education, fleet experimentation, and recent fleet experience. FNMOC is a strong collaborator in this process, bringing unique value as an operational testing ground for some of the ideas emerging from NPS. FNMOC’s projects and products have proven to be fertile ground for NPS thesis work.

FNMOC’s current mission statement is to “Prepare the marine and joint battlespace to enable successful combat operations from the sea. Exploit the meteorological and oceanographic opportunities and mitigate the challenges for naval operations, plans, and strategy at all levels of warfare” (*Fleet Numerical Meteorological and Oceanographic Center (FNMOC), n.d.*).

2. Air Force Weather Agency (AFWA)

With the formation of the United States Air Force in 1947, Air Weather Service (AWS) assumed the responsibility of worldwide weather reporting and forecasting for both the Air Force and the Army. In 1948, AWS moved to Andrews Air Force Base

(AFB), Maryland, and was assigned to the Military Airlift Command (MAC). AWS relocated to Scott AFB, Illinois, in 1958, where it remained for almost forty years. In 1997, AWS was redesignated the Air Force Weather Agency (AFWA) and relocated to Offutt AFB, Nebraska (Powers, n.d.).

AFWA supports the fielding of well-equipped, well-trained Air Force weather units prepared to deliver timely, accurate, reliable weather products. AFWA develops, issues, and evaluates standardized procedures for all Air Force weather units and provides specialized training and technical assistance as required by Air Force and Army customers.

AFWA's production operation involves collecting over 140,000 weather reports per day via the Automated Weather Network. This data is combined with satellites information to constructs a real-time, integrated environmental database and is used by a super computer to model the existing atmosphere and forecast changes (Powers, n.d.).

Like FNMOC, AFWA is not an automated production center, but it is a computer-based operation heavily reliant on the interaction between people and computers to produce accurate and complete services in support of operational requirements. AFWA exchanges data and meteorological products with the FNMOC and the NWS. AFWA also serves as a backup agency for the NWS. Products and services provided by AFWA include meteorological advice; aviation, terminal and target forecasts; prediction of severe weather; automated flight planning; exercise and special mission support; and computations for ballistic missile systems, as well as the collection and dissemination of environmental data (Powers, n.d.). AFWA produces quality, worldwide, mission-tailored terrestrial and space weather products 24-hours a day to meet the requirements of the DOD. AFWA is the DOD’s only space weather analysis and forecast center.

AFWA’s current mission statement is “To arm our nation’s forces with essential air and space environmental intelligence, training, and technical services to ensure battlespace awareness and decision superiority -- anytime, anywhere” (*Air Force Weather*, 2005).

E. NUMERICAL WEATHER PREDICTION (NWP)

1. Introduction

As mentioned before, NWP is the science of using supercomputer to forecast future weather using equation based models of the atmosphere. The process of NWP can be broken down into six basic steps shown below in Figure 17.

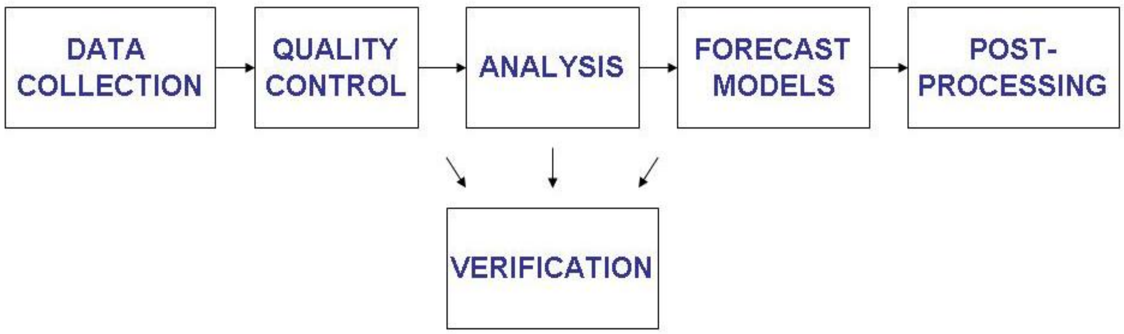

Figure 17. NWP data-collection flow chart used for assembling numerical weather modeling data (From *Meteorology Education and Training*, 2006).

2. Data Collection

Data collection process begins when the model receives environmental data from various reporting stations including ships, buoy reports, surface station reports, aircraft reports, upper air soundings from rawinsondes, satellite-derived products, etc. Satellite data is received from the National Oceanic and Atmospheric Administration (NOAA), Defense Meteorological Satellite Program (DMSP) polar-orbiting satellites, and DMSP Special Sensor Microwave Imager (SSM/I) data. This satellite data provides surface wind speed, atmospheric water vapor, cloud liquid water, and rain rate.

3. Quality Control

Quality control begins once the model receives data. As soon as data are received, they are time stamped and amassed into a database. Then depending on the model, 'data cuts' are taken at various times and all data received after the last cut are removed from the database and prepared for input into the models. Once the data are cut, the validity the observations are checked to ensure they are within a predetermined acceptable physical range of values. Conventional data are subjected to various tests including gross error checking and complex quality control of radiosonde observations

(Baker, 1992; Baker, 1994; Gandin, 1988). Quality control of aircraft data includes sophisticated flight track checking and characteristic error detection (Pauley, 2002).

4. Analysis

After passing quality control, the adjusted model forecast variables are compared to the observations to determine differences that are then entered into an analysis program. The differences are then weighted by a factor based on the reliability of the observations. This weight is determined by several factors including model trend tendencies, climatology, and instrument-error characteristics.

The data is then assimilated where irregularly spaced observations are extrapolated onto a regularly spaced grid. After the data are placed on the grid points they are again verified using the 'first guess' data fields from the previous model forecast. If the data passes this verification step, it is then blended with the 'first guess' fields, a process that maintains dynamic consistency between the analysis and the model.

5. Data Assimilation (not on the diagram)

The purpose of data assimilation is to put irregularly spaced observations into a regularly spaced grid of values to provide data for the forecast models. Data assimilation 'blends' the forecast model's last output with incoming observations. This process defines the initial conditions of the atmosphere and creates a set of initial conditions for the model which agrees with observations. Data assimilation also account for errors associated with each type of observation and weighs these errors accordingly based on the instrument that provided the observation and its historical accuracy.

Data assimilation is not simple interpolation as it uses balanced relationships to introduce dynamical consistency into the analysis. It also filters out scales of motion that the model cannot resolve, maintaining dynamic consistency between the analysis and the model.

6. Forecast Models

This step in the NWP process produces a forecast by integrating the model equations forward in time. In order to integrate the equations in time, the terms in the equations are evaluated and used to predict the conditions a small increment in time later. This small time increment is referred to as the 'time step' and must be short to maintain numerical accuracy (Wendell Nuss, personal communication, December 11, 2006).

7. Post Processing

The post-processing takes output from both the analyses and forecast runs, conducting verification against observations of selected meteorological fields. This step also archives the data in a suitable format. Post-processing begins once a forecast is produced and numerical filters are applied to the raw numerical output. These filters help to eliminate high-frequency noise in the model fields that have not already been removed by damping.

Model output statistics (MOS) are kept on every model run output. These statistics are used to track trends in the model and are used to set model parameters. MOS are based upon long-term model performance statistics and climatological observations. Using this statistical approach, model biases and systematic errors can be identified and eliminated for specific forecast variables and locations.

8. Verification

Model data verification is a continuous process that takes place during the Quality Control, Analysis, and Forecast Models process. As previously discussed, verification compares the current model output to the 'first guess' from a previous model forecast and compares the current output model parameters statistic produced in the model output post-processing.

F. NUMERICAL WEATHER MODELS

The U.S. Navy currently relies on two NWP models to forecast weather. These models are the Navy Operational Global Atmospheric Prediction System (NOGAPS) and the Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS 3.1™). NOGAPS is a synoptic global forecasting model, while COAMPS is a finer mesoscale model. Two of the most important meteorological parameters to the navy are the wind components: speed and direction.

The foundation of NOGAPS' and COAMPS' ability to forecast meteorological events is based on the number and quality of observations ingested into the model. The greater the number of high-quality observations, the better the model resembles the world's atmosphere. Unfortunately, there are many areas of the world where observations are scarce which leads to a poor model forecast.

To understand the NWP process, a summary of the data processing of NOGAPS and COAMPS follows.

1. Navy Operational Global Atmospheric Prediction System (NOGAPS)

NOGAPS, created by NRL/MRY, is a global numerical forecasting model that uses primitive equations to forecast global atmospheric weather. NOGAPS, like many other NWP models, consists of an atmospheric data-assimilation system comprised of data collection, quality control, analysis, verification, forecast model initialization, and postprocessing components.

NOGAPS is important because it provides an operational global weather forecast along with the forcing and boundary conditions for numerous other atmospheric and oceanographic models. These models include COAMPS, ocean wave models, sea ice models, ocean circulation models, ocean thermodynamics models, tropical cyclone models, aircraft and ship-routing programs, and application programs at both FNMOC and the Air Force Weather Agency (*Meteorology Education and Training*, 2006).

The equations of fluid motion are the basis for all NWP models and their simplest forms use pressure coordinates. However, pressure-coordinate systems do not work well when solving forecast equations over varied terrain because surface height, like a mountain, often vertically spans several pressure heights. If a model attempts to extrapolate underground or through some surface feature, the solutions to the forecast equations are not valid. To address the problem, Phillips developed a terrain-following coordinate called the sigma (σ) coordinate illustrated in Figure 18 (Phillips, 1957). In its simplest form, the sigma coordinate is defined by $\sigma = p / p_s$, where p is the pressure on a forecast level and p_s is the pressure at the earth's surface (vice the mean sea level pressure (MSLP)). The lowest sigma coordinate surface is usually labeled $\sigma = 1$ and follows a smoothed version of the actual terrain. As the sigma levels increase in height they tend to straighten out and at the highest sigma level were they are nearly parallel.

In September 2002, NOGAPS' spectral resolution was increased from 159 waves (.75 degree horizontal resolution) to 239 waves (0.5 degree horizontal resolution) and the number of vertical sigma levels was increased from 24 to 30. This increase in horizontal and vertical resolution has improved the model's ability to predict low-level winds, precipitation, and cyclone tracks in the tropics. This increased fidelity has slightly improved its forecast output in the mid-latitudes (Hogan & Clune, 2004).

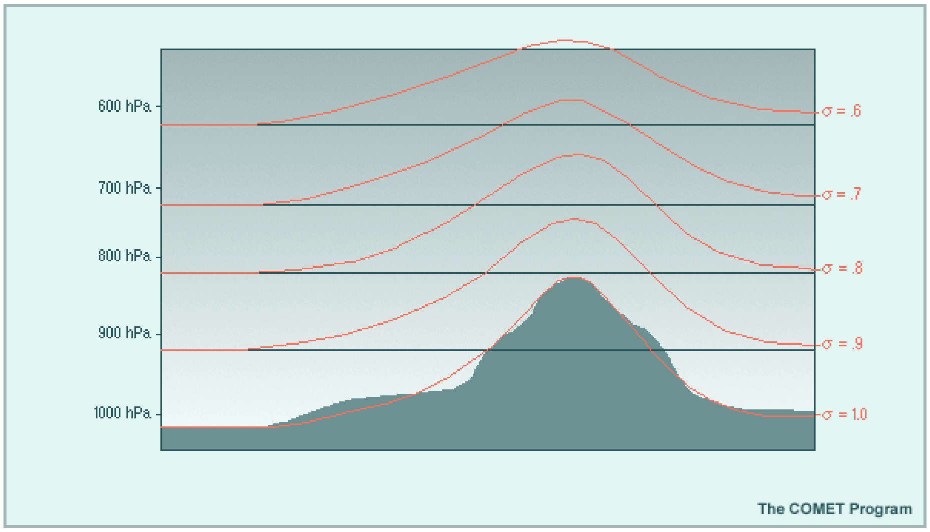

Figure 18. An example of sigma levels that are adjusted and smoothed to account for variations in terrain height (*Meteorology Education and Training*, 2006).

NOGAPS currently has 30 sigma levels with six of the levels located below 850 mb depending on the underlying terrain. On 5 November 2003, NOGAPS' one-degree surface terrain orography provided by the Defense Mapping Agency's Digital Terrain Elevation Data Level 1, which had been used since 1988, was replaced by the half-degree Global Land One-kilometer Base Elevation (GLOBE) data set (Hogan, Pauley, & Teixeira, 2003). NOGAPS' low boundary sigma level follows the surface terrain and terminates between 4 and 7 mb, where the vertical motion is insignificant (Hodur, 1996). One advantage of using sigma levels is that the number of levels can be easily increased.

NOGAPS was the first operational model to use SSM/I wind speeds (Goerss & Phoebus, 1992). NOGAPS also uses high-density multispectral wind observations produced by the University of Wisconsin-Cooperative Institute for Metrological Satellite Studies (*Meteorology Education and Training*, 2006).

In September 2003, the NOGAPS model replaced the Multivariate Optimum Interpolation system (MVOI) with the NRL Atmospheric Variational Data Assimilation System (NAVDAS) for converting satellite data into model input. NAVDAS comprises the data quality control and analysis elements of the new NOGAPS data assimilation system. It is a three-dimensional variational analysis scheme and is the replacement for the MVOI analysis that had been operational at FNMOC since 1988 (Goerss, Hogan, Sashegyi, Holt, Rennick, & Beeck, 2003). NAVDAS is a process by which satellite observations are converted to usable parameters and produces data from the surface to .1 mb. Within the NAVDAS both satellite and conventional data are further checked for quality and consistency, with neighboring observations and the model short-term forecast (*Meteorology Education and Training*, 2006). This process of quality control is referred to as 'buddy checking.'

NOGAPS analysis mathematically models the earth's atmosphere from the surface to a height of 1 mb. However, because the model uses sigma coordinates, the first predictive level is between 4 mb and 7 mb above the underlying terrain (Hogan, 2006). The numerical modeling method for NOGAPS is spectral in the horizontal and energy-conserving finite difference (sigma coordinate) in the vertical. A spectral system allows complicated mathematical equations to be expanded into sines and cosines. These expanded equations can then produce extremely accurate solutions allowing for higher resolution model output. The variables used by NOGAPS' dynamic formulations are vorticity and divergence, virtual potential temperature, specific humidity, surface pressure, ground temperature, and ground wetness. Lower boundary is affected by terrain height, ocean surface, and land roughness. The analysis is performed on the Gaussian grid of the T239 L30 global spectral model with half-degree resolution.

NOGAPS operational forecast runs on a massively paralleled computer system comprised of 120 processors that executes the full global weather model four times a day (Learner, 2006). The model initializes its run three hours before synoptic times (0000Z, 0600Z, 1200Z, and 1800Z) and completes the run approximately 80 minutes after synoptic time. NOGAPS currently outputs close to 25,230 gridded fields per day (Bill Anderson, personal communications, February 25, 2006).

To produce its forecast, NOGAPS uses primitive, hydrostatic equations that are integrated on a 220-second time step. Hydrostatic equations assume that the vertical pressure gradient force is balanced by gravity. However, the time step can be reduced if stratospheric jets go beyond a designated threshold (Jeffery Learner, personal communications, February 23, 2006). NOGAPS provides output data at 16 standard pressure levels: 1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 mb.

2. Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS)

COAMPS was developed by NRL and implemented at FNMOC in 1997 to meet emerging U.S. Navy requirements for tactical METOC analysis and forecast products in the littoral zone (*Fleet Numerical Meteorology and Oceanographic Center (FNMOC)*, n.d.). COAMPS provides the Navy with a finer-scale model that has the ability to decrease the grid size and introduce additional physics, higher-resolution terrain, and local observations. FNMOC currently runs COAMPS for eight regions of the world that are of interest to the DOD and forecasted products are regularly disseminated to Navy, DOD, and other government agencies.

In the littoral zone, phenomena of concern include coastal winds, squalls, near-shore tides, currents, and surf. These phenomena typically occur on a sub-mesoscale and have short life cycles that are strongly influenced by their physical boundaries including coastal terrain, bathymetry, and river outflow. While global numerical models, such as NOGAPS, work well to forecast large-scale, synoptic environmental events, they do not have the resolution or the physical processes required to provide accurate and timely forecasts of the detailed conditions in the littoral zone.

COAMPS provides an integrated system approach to mesoscale analysis and forecasting which is well suited for the littoral zones. Its current operational system uses the same NWP methods as NOGAPS (data quality control, data assimilation, etc.), but there are some distinct differences between the two models. COAMPS has smaller grid spacing, a different sigma coordinate system, uses non-hydrostatic equations, has the ability to ingest local observations, uses MVOI vice NAVDAS for data quality control, and is directly coupled with the ocean model.

COAMPS is designed to use multiple nested grids to represent the evolution of environmental quantities over progressively smaller regions of the world at progressively higher resolution. While NOGAPS provides the initial boundary conditions for the outermost COAMPS nest, each nested COAMPS model run provides the lateral boundary conditions for the next smaller embedded nest. When nested, the resolution of each inner nest is increased by a factor of three, which in turn decreases the size of the nest by a factor of three. In each nest, every third grid in the inner nest corresponds to a grid point in the outer nest.

As of June 2004, COAMPS has a variable grid-point resolution that can either be left at default values of 81, 27, and 9 km resolution from outermost to innermost nest or changed to values appropriate to the forecast situation or regional environment. Due to military operations in South-West Asia, FNMOC runs an operational grid spacing of 54, 18, and 6 km with the 6 km nest over the Persian Gulf. In the future, COAMPS outer grid spacing will be reduced and match the resolution of NOGAPS. This will minimize consistency problems at the boundaries between these two models (Jeffery Learner, personal communication, March 25, 2006).

Unlike NOGAPS, COAMPS uses a pressure coordinate system based on height from the surface to 10 mb. COAMPS uses primitive equations and includes non-hydrostatic effects on an Arakawa C grid, which has better performance regarding geotropic adjustments and divergent flows and can produce forecasts on a smaller scale (Hodur, 1996). Non-hydrostatic equations assume that in the governing mathematical equations the pressure gradient force is not balanced by gravity.

Limitations in COAMPS result from the use of a finite number of grid points over the regional domain, and the parameterization methods required to represent sub-grid scale processes such as convection. Because COAMPS uses non-hydrostatic equations, buoyant forces can be predicted, but the model cannot resolve vertical wind (updrafts, downdrafts, and microbursts). Therefore, convective parameterization is still required and grid-scale buoyant forces are often forecasted in the wrong locations and propagate at incorrect speeds and directions.

Since COAMPS cannot resolve some important features explicitly, tools have been developed using model forecast variables to predict the likelihood that the phenomenon of interest will take place. For predicting the occurrence of convection, examples include the use of the lifted index and Showalter index (*Meteorology Education and Training*, 2006). These use the forecast vertical temperature and moisture profiles from COAMPS to forecast the likelihood of convection in a local area. Data to assist forecasters in assessing the large-scale environment for the possibility of irresolvable but significant local weather phenomena can be produced from the COAMPS output, but are not currently available as FNMOC products (*Meteorology Education and Training*, 2006).

COAMPS has the ability to accept local and remotely sensed observations, which provide vital information about the initial state of the atmosphere and ocean into its model run. These observations are validated using a variety of quality controls, and then combined with a short-range (six to twelve hour) forecast using MVOI techniques to generate analysis products. Pseudo-observations derived from NOGAPS data help to further ensure the integrity of the analyses in data-sparse regions. COAMPS assimilates data on each of its nests independently, allowing the model to extract maximum information from each observation and retain small-scale features between forecast cycles.

At present, COAMPS uses the NRL's MVOI with a six-hour data assimilation cycle (Baker, 1992; Baker, 1994; Goerss & Phoebus, 1992). When quality checking data, the 'first guess' of the initial conditions is taken from either a previous COAMPS forecast or the NOGAPS forecast and is interpolated onto the COAMPS grids and these 'first guess' fields are then updated with real data. It is important to point out that this system of quality control depends on using prior models that are of good quality (*Meteorology Education and Training*, 2006). Other conventional data inputs into COAMPS are subjected to quality control by the same process as NOGAPS.

COAMPS' coupling between the atmosphere and ocean is currently supported in two ways. The data assimilation procedures include an analysis of the sea surface temperature on the COAMPS grid. This provides the meteorological model with sea surface temperature boundary conditions that are fully consistent with the atmospheric analyses. In addition, there is one-way coupling with a wave model where the surface winds generated by the atmospheric model define the time-dependent surface momentum flux for a regional wave model (*Fleet Numerical Meteorological and Oceanographic Center (FNMOC)*, n.d.).

COAMPS products support two general classes of applications: traditional event forecasting and specialized model support. Traditional event forecasting usually involves real-time operations where timeliness is a major consideration, while an example of specialized model support is the 6 km COAMPS nest currently being run over the Persian Gulf where high accuracy is required.

Since October 1997 when limited COAMPS forecasts became available, forecasters at Navy METOC centers, facilities, and aboard ships have come to use it extensively and have described the overall performance of the model as excellent. Although COAMPS provides extremely accurate predictions of some mesoscale events, such as coastally trapped winds, it does not perform well over the open ocean. COAMPS is particularly adept at predicting well-known localized wind events such as the bora, mistral, levante, and shamal (*Fleet Numerical Meteorological and Oceanographic Center (FNMOC),* n.d.).

Full-resolution COAMPS model output is also transmitted in real time to users at selected government agencies. These files provide environmental conditions for very high-resolution atmospheric dispersion models, such as the Vapor Liquid Solid Track and Hazard Prediction and Assessment Capability models (*Fleet Numerical Meteorological and Oceanographic Center (FNMOC),* n.d.).

3. Weather Research and Forecast (WRF) Version 2.0.3.1 Model

The WRF Model is a next-generation mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores, a 3-dimensional variational (3DVAR) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility (*Weather Forecast and Research (WRF) Model,* n.d.).

The development of the WRF modeling system is an ongoing multiagency effort as a collaborative effort among the National Center for Atmospheric Research (NCAR) Mesoscale and Microscale Meteorology Division, NOAA's Nation Centers for Environmental Prediction (NCEP) and Forecast System Laboratory, the Department of Defense's AFWA, and NRL, the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma, and the Federal Aviation Administration (FAA), along with the participation of a number of university scientists (Skamarock, Klemp, Duhia, Gill, Barker, & Wang, 2005).

The WRF model is designed to be a flexible, state-of-the-art, portable code that is efficient in a massively parallel computing environment. The WRF also offers a modular single-source code that can be configured for both research and operations offering numerous physics options. WRF is maintained and supported as a community model to facilitate wide use. In the university community it is particularly used for research and teaching. It is suitable for use in a broad spectrum of applications across scales ranging from meters to thousands of kilometers (Skamarock et al., 2005). Such applications include research and operational NWP, data assimilation and parameterized-physics research, downscaling climate simulations, driving air-quality models, atmosphere-ocean coupling, and idealized simulations including boundary-layer eddies, convection, baroclinic waves, etc (Skamarock et al., 2005).

Real-time mesoscale model forecasts using the WRF model Version 2.0.3.1 are produced forecasting out 48 hours twice a day at the National Aeronautics and Space Administration's (NASA) Short-term Prediction Research and Transition Center. The current model configuration employs a 36 km domain with a horizontal 118 km x 95 km grid that covers the continental United States and a 12 km (121 km x 121 km grid) nest over the Southeast with 37 vertical levels up to 100 mb (Skamarock et al., 2005; *Weather Forecast and Research (WRF) Model,* n.d.). Web products from the WRF are available via the World Wide Web (WWW) at the following link: http://www.wrf-model.org/plots/wrfrealtime.php.

WRF allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. WRF provides operational forecasting a model that is flexible and efficient computationally, while offering the advances in physics, numerics, and data assimilation contributed by the research community.

WRF has a rapidly growing community of users, and workshops and tutorials are held each year at NCAR. WRF is currently in operational use at NCEP. The website provides information on the WRF effort and its organization, references to projects and forecasting involving WRF, and links to the WRF users' page, real-time applications, and WRF-related events.

There are five development teams for the WRF system: Numerics and Software, Data Assimilation, Analysis and Validation, Community Involvement, and Operational Implementation which coordinates efforts from the working groups in a general area of the WRF development process. There are sixteen working groups for the WRF system, each of which concentrates on a particular aspect of the WRF development process. Each of the working groups maintains a web page, accessible from the following link: http://www.wrf-model.org/development/development.php.

G. GLOBAL INFORMATION GRID (GIG)

The GIG is defined as the globally interconnected, end-to-end set of information capabilities, associated processes, and personnel for collecting, processing, storing, disseminating, and managing information on demand. The GIG vision implies a fundamental shift in information management, communication, and assurance providing authorized users with a seamless, secure, and interconnected information environment that will meet all requirements of the warfighter and other users.

The GIG includes all communications and computing systems and services, software applications, system data, security services, and other associated services necessary to achieve information superiority for the U.S. Military and is the manifestation of network-centric warfare (*Global Information Grid* (GIG), 2006).

Figure 19. An artist’s concept of the GIG (From *Global Information Grid*, n.d.).

Although all of the objectives of the GIG have yet to be achieved, computer-enabled communication between soldiers and their commanders on the battlefield during the OIF serves as an example of the functionality of the GIG (*Global Information Grid*, n.d.). The key point to all GIG strategies is that they are based on XML technologies. Thus all of the technical approaches demonstrated in this thesis exactly match other network-centric GIG architecture applications.

H. STUDIES CONCERNING ENVIRONMENTAL EFFECTS OF MUNITIONS

1. Accuracy of Tube Artillery Fired at Extended Ranges

A recent publication concerning the environmental effects on munitions was a Danish Army Artillery School paper that summarizes the outcome of a meeting at the ARL in March of 1997 where a team of experts from the Military Committee Meteorological Group/Working Group-Battle Area Meteorological Systems and Support discussed the technology to enhance the accuracy of artillery fire. This team of experts found that at a range of 35 km, delivery accuracy for predicted fires was expected to have a circular error probability (CEP) of 280 m using radiosonde data that was less than 2 hours old. Their analysis found that using radiosonde data less than one hour old decreased the CEP to 210 m, a CEP error reduction of 25 percent (Minholts & Hansen, 1997).

Of all associated error studies, this report identified meteorology (MET) data as the primary source of targeting error. MET data for this application is composed of three components and the order of greatest effect is: wind, temperature/pressure, and humidity, where wind data is of far greater importance than temperature/pressure and humidity. This report concludes that the main factors influencing the delivery accuracy of artillery fire are meteorology (67 percent), projectile aerodynamics (22 percent), muzzle velocity variations (10 percent), and others (1 percent) (Minholts & Hansen, 1997).

2. BACIMO Conference

At the Battlespace Atmospheric and Cloud Impacts on Military Operations (BACIMO) conference of 2001, Dr. Paul Arthur of the UK MET Office briefed that information on wind speed and direction, temperature, and relative humidity is required by artillery in order to accurately aim the gun. He stated that meteorological errors are responsible for 66 percent of the total artillery error budget (Arthur, 2001). In the UK, this information is typically obtained using a radiosonde data obtained at least 20 km from the required location and typically the data used for firing is older that 2 hrs. To address this problem, the MET Office has created Computerized Meteorological System (CMetS). CMetS will use gridded forecast data from a mesoscale model to provide wind, temperature, and relative humidity data interpolated in space and time along the projectile's trajectory (*Computerized Meteorological System (CMetS)*, 2001).

3. Effects on SADARM Trajectory Simulations with Local RAOBs and BFM Data for the RDAP/LUT Firings

The U.S. Army Research Laboratory (ARL) was tasked in 2002 to perform MET analysis of data collected during the Sense and Destroy Armor (SADARM) Reliability Determination/Assurance Program (RDAP) and Limited User Test (LUT) artillery live firings in January, April, and May of 2000, at Yuma Proving Ground, Arizona (Jameson, Luces, & Knapp, 2002). For this study, SADARM impact data were compared against predicted impacts derived from the General Trajectory Model, Version 3 (GTRAJ3) artillery trajectory simulation program. Two types of MET data were entered in the GTRAJ3 in order to test which type most accurately represented the atmosphere. These data were provided by radiosonde balloon observations (RAOBs) and data generated by the Battlescale Forecast Model (BFM) which uses NOGAPS' data to provide it initial and boundary conditions.

The SADARM RDAP and LUT firings were at a range slightly less than 20 km and were aimed with RAOB data that was less than two hours old. The study found that even during optimum conditions for using these observations that the BFM forecasts outperformed the RAOBs in accurately representation the atmosphere (Jameson, Luces, & Knapp, 2002). The study concludes that modeled MET data is valid for future live artillery firing.

4. Artillery Firing Simulations using "Met-Along-The-Trajectory" (MATT)

In May 2004 the ARL conducted an analysis to determine the suitability of mesoscale MET computer model output for artillery aiming application using "Met-Along-The-Trajectory" (MATT). Currently Army battlefield doctrine calls for the used of RAOBs to produce data for formatted as Computer MET Messages (CMMs).

Previous ARL studies have shown that CMMs derived from mesoscale weather Forecast MET Models (FCMMs) are more accurate than CMMs derived from RAOBS Forecasted MET Models (RCMMs).

This report considers whether simulated artillery firing accuracy might be increased by acquiring MET data from a model at a number of points along the trajectory path. Simulations from the GTRAJ3 were run to evaluate the accuracy of the three types of MET data based on a RAOBs, model-derived data at three points on the flight path (firing location, apogee, and target location), and MATT-derived from the BFM (Jameson & D'Arcy, 2004).

The GTRAJ3 data were compared against live-fire impact data, for a firing range of 41 km, to determine which type of MET data was the most accurate. In all of the firing simulations, the modeled FCMMs representing three points along the trajectory were more accurate than RCMMs. The modeled CMMs reduced the radial miss distance by 48 percent. Applying the MATT methodology further improved that figure by another 7 percent. ARL believes that higher resolution datasets for longer firing ranges might yield better results for the MATT data, but were not available at the time (Jameson & D'Arcy, 2004). The ARL report concluded that future long-range artillery firings needed to use MATT methodology and NWP model data to improve its accuracy.

5. Navy Ballistic Meteorological Data Study

The Firing Tables and Ballistic Division (FTAB) of the U.S. Army Armament Research, Development, and Engineering Center (ARDEC) were tasked by the NSWC-DD in 2004 to compute a ballistic MET error budget for NGFS. This error budget is compared to the Navy’s current error budget values which are used to estimate the accuracy of naval gunfire. The differences (forecasted MET minus observed MET) in the ballistic forecast components (wind direction, wind speed, air temperature, and air density) are derived and the distributions are described in this report (Bellamy, Matts, & Andriolo, 2004).

This statistical study provided two conclusions: MET data used in operations should be no longer than two hours old and global atmospheric weather models (such as NOGAPS) are capable of forecasting ballistic MET data valid for NGFS (Bellamy et al., 2004).

6. Method of Checking Weather Information for Operational needs of Artillery

This study was conducted in 2005 by the MARTEC Company for the French military administration concerning using weather data for fire control input. The study states that NATO regards numerical modeling as a way to extend, in space and time, the validity of the atmospheric effects on ballistic trajectories and that the community of ballisticians believes that two thirds of firing error can be attributed to weather uncertainty (Bézard, Bholah, Collin, Delplanque, Pettré, & Segers, n.d.).

The authors believe that when firing artillery at long ranges (up to 100 km) numerical weather forecasts will have to be used in the firing solutions to keep the absolute firing error to a minimum. They state that this point was highlighted at the CoMETfire test campaign, carried out in Denmark by NATO in September 2003.

The authors believe that an implementation using NWP for military units in the field requires support for the follow criteria to be successful:

- Assuming there will be no forecast expert on site, there needs to be a simple, fully automated method of receiving environmental data.
- The data must be easily communicated and readily available.
- The data needs to be directly delivered to the weapon system in a usable format without any interpretation.
- The amount to data sent must be minimal.
- In a context of inter-army (ally) collaboration, the fire control system must be capable of receiving best data from various forecast models.

MARTEC proposed a tool that would be able meet criteria outline above. This tool would basically make a comparison of the digital outputs of models coming from one or more weather centres with the data resulting from field observations (Bézard. et al., n.d.).

I. SUMMARY

The history of computers, ballistics, and NWP is intrinsically linked as the first computer was created to calculate environmental effects on projectile ballistics and this computer was later used to produce the first NWP forecast. There is a direct relationship between computer processing capability and the accuracy of NWP. As shown in Figure 15, as the number of available computer processors increase, so does the accuracy of NWP.

Currently there are two types of environmental data available for long-range gunfire support: radiosonde data and NWP. Of the six studies relating projectile performance error and environmental data, the following conclusions are the most significant for long-range gunfire support:

- Approximately 66% of ballistic error can be attributed to meteorological factors.
- The most important environmental factors is wind (speed and direction), temperature, and pressure (air density can be calculated from temperature and pressure).
- Using radiosonde data less than one hour old decreases CEP error by 25%.
- Data from global atmospheric weather models is suitable to be used for ballistic corrections.
- Model generated NWP data was found to outperform on scene collected radiosonde data.

IV. EXTENDED-RANGE MUNITION (ERM) DYNAMIC MODELING

A. INTRODUCTION

This chapter covers the design of the 5DOF model and the use of the AUV Workbench to create a ballistic correction for the ERM.

B. 5 DEGREE OF FREEDOM (5DOF) MODEL

1. Extended-Range Munition (ERM) 5 Degree of Freedom (5DOF) Model

Adaptation and implementation of the ERM 5DOF model is described in *Modeling Extended-Range Munitions (ERMs) in the Autonomous Unmanned Vehicle (AUV) Workbench* (Wahl, 2006). In summary, the aerodynamic coefficients for an ERM-like projectile were defined with arrays created to hold the simulation output data. Next, initial conditions were calculated, grouping significant terms together appropriately in four categories: environmental, acceleration, velocity, and position coefficients. Next dynamic equations of motion, using a loop to forward the time-step, calculated new values. A loop break was used to stop the program when the projectile hit the ground when its altitude became negative. Figure 20 summarizes the model's algorithm.

- Set parameters
- Initialize position arrays
- Calculate initial conditions
- Emulation timing loop, repeat until complete
    - Calculate updated environmental variables
    - Calculate updated accelerations
    - Calculate updated velocities
    - Calculate updated positions and orientation
    - Calculate updated spin rate
    - Break loop when projectile impacts ground

Figure 20. Projectile real-time dynamic modeling algorithm (From Wahl, 2006).

2. Extended-Range Munition (ERM) 5 Degree of Freedom (5DOF) Model Design Implementation

a. Factors Accounted and Not Accounted for by the ERM 5DOF

The ERM 5DOF model is an accurate but not perfect simulation of an ERM. This model accounts for acceleration, gravity, and drag, while the simulation's predefined aerodynamic coefficients account for Magnus force. To make the model output more realistic, the environmental values for this simulation were derived from the Standard Atmosphere, 1976.

In this model, yaw (Ψ) is kept constant and limits this model to a 5DOF model vice a full 6DOF. Another shortfall of this model is that it does not precisely approximate the mass reduction due to the consumption of rocket fuel during the rocket-boost phase. The 5DOF also does not correctly account for the time characteristic of thrust of the rocket-boost and is simulated as instantaneous force.

b. ERM 5DOF Model Output Results

Specific BTERM flight data is considered to be proprietary information by ATK, however, open-source flight path data is available in *Naval Fires in Support of Expeditionary Maneuver Warfare* (Marsh, 2005) as illustrated in Figure 5. This source provides a TOF of approximately 3 minutes (180 s), an apogee of approximately 36,500 m, and a maximum range of approximately 118,500 m for the BTERM and this data was used as a benchmark for all 5DOF simulation output.

Table 3 summarizes overall errors in the key parameters between BTERM open-source data and the output from the Java/Workbench 5DOF simulation. It is believed these errors are attributable to the method by which the rocket-boost acceleration and mass decrease is modeled in the Java 5DOF simulation.

Table 3. Data magnitude comparison between open-source data and the 5DOF simulation in both Java and the AUV Workbench (From Wahl, 2006)

Data Source	Range (m)	Apogee (m)	TOF (sec)	Lateral Drift (m)
BTERM (open-source)	~118,500	~36,000	~180	No data available
Java 5DOF model / AUV Workbench Simulation	121,049	33,455	187	2,198
Percent Deviation	2.15%	7.07%	3.88%	--

3. Autonomous Unmanned Vehicle (AUV) Workbench

The NPS AUV Workbench supports physics-based dynamic modeling and visualization of vehicle behavior and sensors in multiple environments. The AUV Workbench allows animation based on vehicle-specific hydrodynamics or aerodynamics that can be configured to model a variety of vehicles. Visual models created in 3D computer graphics such as X3D (extensible 3D graphics standard) and Virtual Reality Modeling Language (VRML) use the Institute of Electrical and Electronics Engineers, Inc (IEEE) Distributed Interactive Simulation (DIS) Protocol is used to communicate state updates for these models across the network. Results are displayable utilizing custom software or off-the-shelf web browsers (Lee, 2004). The AUV Workbench provides a virtual environment for the development of robot control algorithms, emphasizing realistic mission generation, rehearsal, and replay of completed missions in a laboratory environment.

Graphical mission generation in the AUV Workbench provides automated generation of mission specifications in an XML and Autonomous Vehicle Control Language (AVCL). AVCL is based on a command language supporting mission scripting and vehicle-to-vehicle, vehicle-to-agent, and vehicle-to-human communications that has the capability to store runtime telemetry data (Davis, 2006; Lee, 2004). The AUV Workbench allows for the automated conversion of XML missions into text-based AUV command languages using XSLT transformation. It also allows the efficient serialization and transmission of generated imagery, telemetry, and reports using XML Schema-based Binary Compression (XSBC) providing communications protocol between remote vehicles and individual operators in both the virtual and real world. The AUV Workbench autoinstaller is publicly available and can be downloaded via http://web.nps.navy.mil/~brutzman/.

C. SOUTHERN CALIFORNIA OFFSHORE RANGE (SCORE)

The SCORE range is centered on San Clemente Island (SCI) located off of the coast of San Diego, California. SCORE is controlled by the Fleet Area Control and Surveillance Facility, San Diego (FACSFACSD), which is located on the Naval Air Station North Island (NASNI). All SCORE operations are monitored, controlled, and evaluated by Range Operations Center (ROC) personnel at NASNI (Pike, 2005).

SCORE is a state-of-the-art, multi-warfare, integrated training facility used to support the Commander of Third Fleet (CTF) and the Commander of Naval Air Force, U.S. Pacific Fleet's training and readiness requirements (Pike, 2005). SCORE supports an extensive range of exercises, including surface ship Over-The-Horizon Targeting (OTH-T) exercises, Antisubmarine Warfare (ASW) exercises, Mine Warfare Exercises (MINEX), Strike Exercises (STRIKEX), Electronic Warfare (EW) exercises, and NSFS exercises. SCORE can currently support up to five concurrent unit-level exercises from the ROC (Pike, 2005). SCORE is also is used for testing, evaluating, and development of weapon systems and tactics.

The Shore Bombardment Area (SHOBA) is located on the southern tip of SCI as illustrated on Figure 21. SHOBA is used to conduct strike warfare, close air support, laser targeting, naval gunfire, small arms, and special warfare operations (Pike, 2005). The Expeditionary Warfare Training Group, Pacific (EWTGPAC) personnel use SHOBA to conduct Fire Exercises (FIREXs) to train and evaluate NSFS ships and spotters. EWTGPAC also uses SHOBA to conduct coordinated supporting arms exercises involving artillery, mortars, and close air support.

SHOBA is the only NSFS range located on the west coast of the U.S. When ERMs are deployed, their firing ships will be trained and evaluated at the SHOBA. Thus, for this project the area surrounding SCORE was included in the bounding box to receive FNMOC GRIB data and import it into the AUV Workbench.

NPS has also received digital terrain data for SHOBA, which is being processed for integration into the AUV Workbench.

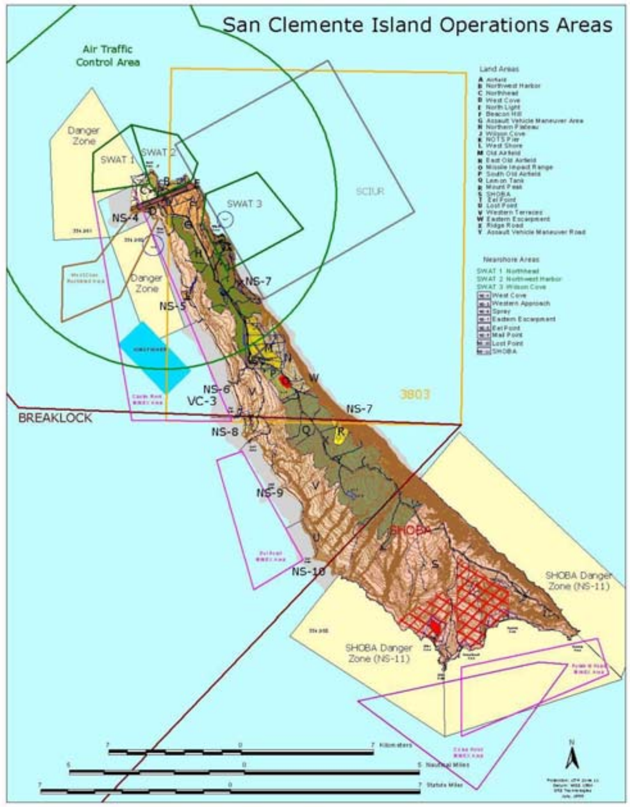

Figure 21. San Clemente Island Operations Areas. Note the SHOBA area located at the southeast end of the island (From *San Clemente Island*, n.d.).

D. ENVIRONMENTAL DATA BENCHMARK

In order to research the effects that FNMOC's NWP output pressure and temperature error might have on the ballistic flight path of a projectile, a benchmark using U.S. Standard Atmosphere, 1976, data was created using the ERM 5DOF. After this benchmark was established, each parameter in question was varied in accordance with the estimated model output data error range. Data for this benchmark is shown below in Table 4 where it is convenient for side by side comparison.

The FNMOC NWP model output error estimate was provided from *The Multivariate Optimum Interpolation Analysis of Meteorological Data at the Fleet Numerical Oceanography Center* (Goerss & Phoebus, 1993). Additional input was provided by personal communications with both Dr. James Goerss and Dr. Wendell Nuss. Both of these individuals are subject matter experts in FNMOC model output.

Table 4. Benchmark trajectory data results of the ERM 5DOF using atmospheric parameters provided by the U.S. Standard Atmosphere, 1976.

Range (m)	Apogee (m)	TOF (s)	Lateral Drift (m)
121,049.4	33,455.4	186.6	2,198.2

E. ENVIRONMENT DATA COLLECTION

Using data available in *The Multivariate Optimum Interpolation Analysis of Meteorological Data at the Fleet Numerical Oceanography Center* (Goerss & Phoebus, 1993) and consulting with FNMOC model experts, it is estimated that a typical FNMOC model error output for pressure and temperature is typically +/- 2.5 mbar (Wendell Nuss and James Goerss, personal communication, October 15, 2006).

F. DATA ANALYSIS

While all other initial conditions were kept constant in the ERM 5DOF model run, varying the initial condition of pressure by plus or minus 2.5 mb (250 Pa) showed no change in the critical parameters. The same test was performed with temperature by varying it plus or minus 2.5^{o} K showed no change in the critical parameters. The results of these experiments are found in Table 5.

Table 5. Comparison of ERM 5DOF model benchmark found in Table 4 to ERM 5DOF model output while varying expected NOGAPS model forecast error.

Parameter	Benchmark Value	Temperature		Pressure	
		+ 2.5^{o} K	-2.5^{o} K	+2.5 mb	-2.5 mb
TOF (s)	186.6	No Change	No Change	No Change	No Change
Apogee (m)	33,455.4	No Change	No Change	No Change	No Change
Range (m)	121,049.4	No Change	No Change	No Change	No Change
Lateral Drift (m)	2,198.2	+ .7 m	- .7 m	No Change	No Change

G. SUMMARY

A comparison of ERM open-source trajectory data and trajectory data produced by the ERM 5DOF model is illustrated in Table 3 and shows that the ERM 5DOF correctly models an ERM’s trajectory within 8 percent. Using environmental parameters defined in the U.S. Standard Atmosphere, 1976, a benchmark for all 5DOF simulation output was created and is illustrated in Table 5. Typical FNMOC NWP model output error was then compared using the ballistic model revealing that that these errors have an insignificant effect on the projected results for the ERM 5DOF model. Thus the methodology presented on this thesis to apply environmental data to ballistics show that the best-case solutions are available now.

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V. PRODUCING BALLISTIC CORRECTION (BALCOR) FOR THE EXTENDED-RANGE MUNITION (ERM)

A. INTRODUCTION

There are currently two ballistic wind correction applications used in the fleet. These are the ballistic parameters (BALPARs) application which is used for ballistic missile reentry and ballistic winds (BALW) application which is used by the MK 45 GWS. This chapter describes standard NWP data, how BALW applications work, and ways to communicate their data.

B. STANDARD NUMERICAL WEATHER DATA

1. GRIB Data

In 1985, the World Meteorological Organization (WMO) Commission for Basic Systems (CBS) approved a general purpose, bit-oriented data exchange format which was designated FM 92-VIII Ext. GRIB (GRIdded Binary data format) which is commonly referred to as 'GRIB' data (Dey, 2002). The system compresses environmental data into the GRIB code format making it more efficient to exchange, store, and retrieve.

Each GRIB data set received from FNMOC contains a single environmental parameter at a designated vertical pressure level that is bounded on four sides by latitude and longitude coordinates provided by the requestor. Once that data is amassed, they are encoded into a binary array and sent to the requestor as a continuous bit stream.

Logical divisions of this record are designated into "sections", each of which provides control information and/or data (Dey, 2002). A typical raw GRIB record is shown in Figure 22 and consists of six sections:

(0) Indicator Section

(1) Product Definition Section (PDS) as shown in Figure 23.

(2) Grid Description Section (GDS) – optional and shown in Figure 23.

(3) Bit Map Section (BMS) – optional and not shown in Figure 23.

(4) Binary Data Section (BDS) – decoded and shown in Figure 23.

(5) '7777' (ASCII Characters)

```
47 52 49 42 00 00 be 01  00 00 2e 03 3a 3a 38 80
0b 64 00 04 06 0b 03 0c  00 01 00 00 00 00 00 00
15 00 00 02 00 00 00 00  00 00 00 00 00 00 00 00
63 00 00 00 00 01 00 00  34 00 ff 00 00 0a 00 06
00 7d 00 81 d8 a8 80 00  86 c4 81 c7 14 01 f4 01
f4 40 00 00 00 00 00 00  00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00  00 00 00 00 50 0c 00 00
44 59 72 00 09 c9 df 2c  b4 b9 64 25 de ed 83 cb
ad 14 e9 a4 5d e6 cd 5a  ae 1b 10 39 d4 6d f8 da
59 a4 50 28 f5 ab 76 10  e2 5e 25 4e 25 92 c1 c9
32 b7 69 a9 0e e4 f1 a0  b4 7c 60 40 22 93 a6 51
90 34 00 0e 17 94 cc 65  10 00 37 37 37 37
```

Figure 22. An excerpt of raw GRIB data.

In this documentation, certain symbols are used to clarify the contents of bytes which are referred to as octets in the NCEP documentation. Unadorned letters are described in the text, a decimal number is printed as is, and a character or string of characters is represented inside single quote marks. The U.S. National Standard 7-bit American Standard Code for Information Interchange (ASCII) is used for character-data representation in the GRIB code (Dey, 2002).

Although the GDS is indicated as optional, it is highly desirable that it be included in all messages as it defines the correct geographical grid for each field (Dey, 2002). The majority of weather centers, who are the main GRIB customers, require bulletin headers to enable them to receive, identify, and switch messages (Dey, 2002). More information can be found at NCEP's website: http://www.nco.ncep.noaa.gov/pmb/docs/on388/ or at The Weather Processor website: http://wxp.unisys.com/Appendices/Formats/GRIB.html.

Typically the raw GRIB data is decoded in the standard format with the header illustrated in Figure 23 and the data illustrated in Figure 24. A Java GRIB data decoder provided by Unidata (available at http://www.unidata.ucar.edu/software/decoders) was used to decode the following data.

```
                   Header : GRIB1
               Discipline : 0 Meteorological Products
             GRIB Edition : 1
              GRIB length : 218
        Originating Center : 58 Fleet Numerical Meteorology and Oceanography Center
    Originating Sub-Center : 0 WMO Secretariat
        Product Definition : 0 Forecast/Uninitialized Analysis/Image Product
        Parameter Category : -1 Meteorological Parameters
            Parameter Name : 7 var7 geometric thickness of layer
           Parameter Units : gpm
            Reference Time : 2006-11-27T12:00:00Z
                Time Units : hour
      Time Range Indicator : product valid at RT + P1
              Time 1 (P1) : 0
              Time 2 (P2) : 0
   Generating Process Type : 58 Unknown
                Level Type : 100 isobaric
             Level Value 1 : 200.0
             Level Value 2 : 0.0
               GDS Exists : true
               BMS Exists : false
     Number of data points : 66
                Grid Name : Latitude/Longitude Grid
                Grid Shape: 0 spherical
     Spherical earth radius: 6367.47
                       Nx : 11
                       Ny : 6
                      La1 : 32.0
                      Lo1 : -121.0
Resolution & Component flags : 128
                      La2 : 34.5
                      Lo2 : -116.0
                       Dx : 0.5
                       Dy : 0.5
             Scanning mode : 64
```

Figure 23. Decoded GRIB data header. Note that the decoder used incorrectly translated the 'Parameter Name' which should read geometric height vice geometric thickness of layer.

```
data[ 0 ]=11871.5
data[ 1 ]=11860.63
data[ 2 ]=11849.91
data[ 3 ]=11839.851
data[ 4 ]=11830.54
data[ 5 ]=11822.41
data[ 6 ]=11815.8
data[ 7 ]=11809.9
data[ 8 ]=11804.5205
data[ 9 ]=11801.3
data[ 10 ]=11800.98
data[ 11 ]=11857.72
data[ 12 ]=11846.75
data[ 13 ]=11835.88
data[ 14 ]=11825.41
data[ 15 ]=11815.641
data[ 16 ]=11807.38
data[ 17 ]=11800.55
data[ 18 ]=11794.01
data[ 19 ]=11787.97
data[ 20 ]=11783.98
```

Figure 24. An example of decoded BDS GRIB data corresponding to the header file found in Figure 23. The complete decoded data set contains 66 data points and due to its length only a short segments is shown.

0 11,871.5	1 11,860.63	2 11,849.91	3 11,839.85	4 11,830.54	5 11,822.41…	6	7	8	9	10
11	12	13	14	15	16	17	18 ...11,794.01	19 11,787.97	20 11,783.98	21
22	23	24	25	26	27	28	29	30	31	32
33	34	35	36	37	38	39	40	41	42	43
44	45	46	47	48	49	50	51	52	53	54
55	56	57	58	59	60	61	62	63	64	65

Figure 25. The decoded GRIB data in Figure 24 breaks down into an 11 by 6 matrix of geometric height values as define by Nx and Ny in Figure 23. In the illustration above, the large number in 12 point font is the data point index, while the smaller number in 8 point font is the geometric height in meters of the 200 mb pressure level.

C. CURRENT BALLISTIC FORECAST MODELS

1. BALPARS

The Trident I and II Submarine Launched Ballistic Missiles (SLBMs) are deployed with a ballistic reentry system. The reentry atmospheric environment, such as air density and winds, affects the trajectory ballistics of the Multiple Independently-Targeted Reentry Vehicles (MIRV) after they are released from the missiles section. Once released, the MIRVs have no control surfaces or guidance system and their flight path to the target is purely ballistic. In order to make the MIRVs as accurate as possible, FNMOC computes BALPARs for the Trident I and II SLBM fire control system.

BALPARs are calculated using NOGAPs to produce predicted atmospheric parameters over the target. These messages contain atmospheric data specified at thirteen levels in a 10 km by 10 km grid and include time and earth orientation data that is utilized by the launch platform (*Fleet Numerical Meteorological and Oceanographic Center (FNMOC)*, n.d.). When required by fleet operations, these messages are produced by the FNMOC twice a day or as required by the NSWC-DD and are used operationally by all

SSBNs. To the extent possible, compensation for the environmental effects are included in the missile's presetting which the launching vehicles' Fire Control System (FCS) computer.

2. Ballistic Winds (BALW)

As a projectile travels to its target, it is affected by environmental factors such as changes in atmospheric temperature, density, and wind. For short ranges with the ballistic apogee not exceeding 300 m (1000 ft), direct fire systems, surface environmental data required to calculate the correct aiming offsets can be obtained from local sensors such as an anemometer and a weather vane for measuring wind speed and direction. However, for longer-range indirect fire systems, upper-air environmental data are needed and must be obtained through forecasts and/or measurements to predict upper-air weather conditions. Such predictions are necessary for long-range naval gun fire as it is often conducted over long ranges through several atmospheric layers.

To calculate these environmental corrections, FNMOC has a BALW application (also referred to as the METBAL or BALWIN application). BALW is short for Ballistics Winds and pronounced "ball winds." This application uses numerical weather prediction to provide environmental correction factor for the firing of this gun.

The BALW application calculates ballistic density, temperature, and wind-correction factors required for naval and artillery gunfire support to ensure more accurate aiming with initial firing. These ballistic correction factors are used by GWS, such as the MK 34, to compensate for the deviation of the atmospheric conditions from a standard atmosphere. The BALW application divides the atmosphere into fifteen zones from the surface to 18,000 m and calculates the ballistic density, temperature, and winds for each level along projectile's trajectory (*Software Design Document (SDD) for the Meteorological Ballistic (METBAL) Model,* 2001).

BALW application produces the correction factors and generates a ballistic message prior to the initial firing. The ballistic correction factors are derived from a met profile that contains forecast values for air density, air temperature, and wind velocity valid at the date, time, and location of the scheduled weapon shoot (*Software Design*

Document (SDD) for the Meteorological Ballistic (METBAL) Model, 2001). BALW obtains the required forecast data from the COAMPS or NOGAPS.

BALW messages may be generated for weapon firings up to 72 hrs in the future. Ballistic correction factors are presented as forecast messages in a format suitable for input to fire control systems. Table 6 contains the message formats available for the indicated projectiles. Additional information on the Computer Met and Ballistic Met messages may be found in *Tactics, Techniques, and Procedures for Field Artillery Meteorology*, FM 6-15/MCWP 3-16.5, Headquarters, Department of the Army, Washington, DC, 13 Aug 1997.

BALW application supports surface-to-surface (STS) firing and surface-to-air (STA) antiaircraft firing (*Software Design Document (SDD) for the Meteorological Ballistic (METBAL) Model*, 2001). The most accurate BALWs support messages are based on short-term forecasts of the expected conditions for a period of 6 to 12 hrs based on the environmental data available and the type of model run used.

As currently written, the BALW application can be applied to naval gunfire and marine or army artillery. The naval messages are in U.S. Navy and NATO Ballistic format for the 5-inch and 76 mm naval guns. The artillery messages are generated in Tactical Fire (TACFIRE) and standard format. However, this data can be put into any format that the user requests depending on what is acceptable by their gun weapon system.

Table 6. Standard BALW message formats (From *Software Design Document (SDD) for the Meteorological Ballistic (METBAL) Model*, 2001).

Message	Type
J/VMF	Binary
Package 11 VMF	Binary
Ballistic MET	Standard
Computer MET	Standard
Ballistic MET	TACFIRE
Computer MET	TACFIRE
NATO	Text
U.S. Navy	Text

Input into the BALW application consists of an upper-air profile created by a software application. To convert a meteorological profile into ballistic parameters, the met profile is first divided into eighteen altitude zones as defined by NATO and the midpoint value of the environmental conditions of each zone is determined (*Software Design Document (SDD) for the Meteorological Ballistic (METBAL) Model*, 2001). A system of weighting factors is applied to the profile for the gun/artillery projectile of interest. There is a weighting factor for each altitude layer that the projectile will travels through. The sum of the weighted mid points gives the ballistic value (*Software Design Document (SDD) for the Meteorological Ballistic (METBAL) Model*, 2001). Simply stated, the met conditions in different altitude zones are weighted to give a constant value for each met parameter (wind, density, and temperature) that has the same effect on the projectile during its flight as the varying conditions are encountered by the projectile. Because the maximum apogee (or aircraft target altitude) is not known in advance, correction factors are calculated for all zones, each of which represents a potential maximum apogee.

D. METHODS OF COMMUNICATING NUMERICAL WEATHER DATA

1. Naval Message System

BALPARs are produced at FNMOC on demand when requested by NSWC-DD via a naval message covering a specific area and time period. The BALPARs data are then computed by FNMOC and returned via naval message. BALWs are also available to users via navy message through the same process, but are now available through the FNMOC's homepage.

2. Communication through the WWW via Fleet FNMOC's Webpage

a. Ballistic Winds (BALW) Application

Prior to 2002, BALW data could only be obtained by sending a naval message to FNMOC requesting BALW data. The turn around on this method of receiving BALW data was at least 48 hrs. In 2003, a project was then undertaken to web-enable the BALW application which is currently available via FNMOC Level I secure homepage either by NIPR (unclassified) or SIPR (classified) network. The web address is https://www.fnmoc.navy.mil/. Level I access user name and password can be obtained by contacting the Command Duty Officer at FNMOC.

Accessing the ballistic data link allows the user to enter their message format type, message valid time, firing unit's location, and data message format. At any time the requestor can change the message format and once the message is complete it can be downloaded. The ballistic data take approximately 40 to 80 seconds to compute depending on FNMOC's system load. This project was field tested during Trident Warrior 2003 and lauded as an ideal example of how web-services can quickly and effectively bring true network-centric warfighting capabilities to bear on tactical operations by evaluators on USS Essex (LHD 2) and USS Chancellorsville (CG 62).

3. Advanced Field Artillery Tactical Data System (AFATDS)

AFATDS is a multi-service U.S. Army/Marine Corps automated command and control (C2) system that provides battlefield fire support (Boutelle & Filak, 1996). AFATDS was to processes, analyzes, exchange, and deconflict combat information within the fire support architecture and the joint environment providing safe, timely, and effective fires delivered against enemy targets in accordance with the commander's guidance. AFATDS includes interoperability with Army battle command systems, coalition systems, Marine Corps command, control, intelligence and sensor systems, the Air Force's Theater Battle Management Core System, and the Naval Fires Control System (Palmer, 2004). AFATDS was created with the capable of managing and tasking weapon systems from the joint community, including field artillery, rockets, naval gun fire support, mortars, rotary wing and fixed wing attack platforms.

AFATDS is an integrated fire support command and control system that has been designed to replace the Army's Tactical Fire Direction System (TACFIRE) (Boutelle & Filak, 1996; *Advanced Field Artillery Tactical Data System (AFATDS)*, 1998). AFATDS provides processing capabilities from Fire Coordination Center (also referred to as the Fire Direction Center) using a distributed process with the capability to match fire missions with the lowest echelon capable and available to engage a target (Palmer, 2004). During battle, AFATDS provides up-to-date battlefield information, target analysis, and unit status, while coordinating target damage assessment and sensor operations.

Integrating all fire support systems via a distributed processing system creates tactical mobility for fire support units and allows missions to be planned and completed in less time. AFATDS is also capable of meeting field artillery needs by managing critical resources (such as resupply); supporting personnel assignments; collecting and forwarding intelligence information; and controlling supply, maintenance, and other logistical functions (*Advanced Field Artillery Tactical Data System (AFATDS)*, 1998).

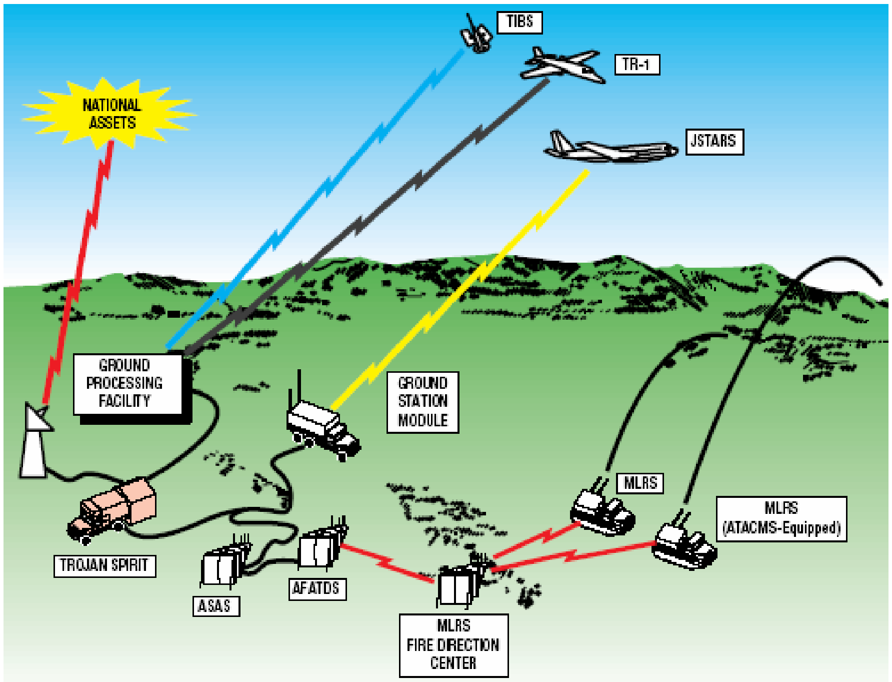

Figure 26. AFATDS: National, Strategic, and Tactical sensors linked to a Joint Fire Support Weapon System providing target data to the Army's Multiple Launcher Rocket System (From Boutelle & Filak, 1996).

On the battlefield, the AFATDS provides operators with a complete look at all the engagement target options available to attack a target. AFATDS provides functionality in four major areas: situational awareness, battle planning, battle management (execution), and fires/effects processing (Palmer, 2004). It provides target analysis and weapon selection logic that ensures that the right munitions are placed on the right target at the right time.

AFATDS V6.3.1 was released in January 2003 and was deployed for use in OIF (Palmer, 2004). In support of the release, requests for enhancements and problems identified were reported back to Raytheon through various methods via the Raytheon Field Integration Team (RIFT) where Raytheon engineers were on site to update the software and provide fixes. At the RIFT, Raytheon's engineers used able to use customer input to recreate and debug the problem in a lab environment.

During OIF, AFATDS directed the firing of more than 35,000 rounds of munitions, 857 rockets, and 453 long range missiles, without a single incident of fratricide (Palmer, 2004). AFATDS' coordination of air space allowed friendly fixed-and rotary-wing aircraft to safely and simultaneously engage enemy targets along with friendly rockets and missiles without the loss of an aircraft due to friendly fire (Palmer, 2004). Besides preventing friendly fire accidents, AFATDS' management of fire support assets also saved a significant amount of money in the optimal use of weapon systems and ammunition.

4. Extensible Markup Language (XML)

a. Background

XML is a technology concerned with the description and structuring of data. XML is a subset of the less successful Standard Generalized Markup Language (SGML) which is a complex text-based language used to add descriptive data (or metadata) to a larger data set. SGML was not a success because it was not well suited for use over the internet; the less-complicated XML matched 80% of the functionality with 20% of the overhead (Hunter, Watt, Rafter, Cagle, Duckett, & Patterson, 2004). In essence, XML is not an actual computer language itself, but rather a standard metalanguage for describing the syntax of other computer languages. XML provides a text-based method to describe and apply a tree-based structure to information. At XML's lowest level, all information is recorded as text interspaced with markups that indicates the information's separation into a hierarchy of character data, container-like elements, and attributes of those elements (*Extensible Markup Language (XML),* 2006).

The fundamental unit in XML is the 'character' as defined by the Universal Character Set (UCS) which is joined in serial combinations to form an XML document. This document consists of one or more entities, each of which is typically some portion of the document's characters, encoded as a series of bits and stored in a test file (*Extensible Markup Language (XML),* 2006). XML files may be served with a variety of media types.

Prior to XML, there were few data-description languages that were general purpose, Internet friendly, and easy to learn and use. At this time, most data sharing formats were proprietary, special-purpose formats based on binary code which was unreadable by humans and was not easily shared between different software applications or across different computing platforms (*Extensible Markup Language*

(XML), 2006). Now that XML is widely accepted, there are many types of text file authoring software, such as word processor and text editors, that facilitates rapid XML document authoring and maintenance.

The general syntax of such XML is flexible, but strict and documents must adhere to its general rules so other XML-capable software can at least parse or read and understand the relative arrangement of information within them. XML makes no prohibitions on how it is used. The beauty of XML is that allows users to either create their own structure or to use an agreed-upon, well-accepted, or already-published XML syntax.

XML schemas typically restrict element and attribute names and the data contained in their hierarchies. Such an example would be allowing the element named <coin> to contain one element from a list of specific coins such as quarter, dime, nickel, or penny. The constraints in a schema may also include data type assignments that affect how information is processed. For example, the <coin> element's data may be defined as only containing U.S. currency in general circulation. In this way, XML contrasts with HTML, which has a single-purpose vocabulary of elements and attributes designed for page presentation that, in general, cannot be repurposed (*Extensible Markup Language (XML)*, 2006).

b. Pertinent Extensible Markup Language (XML) Strengths

The following features of XML make it well suited for data transfer: its syntax is both human and machine readable; it supports Unicode which allows almost any information in any human language to be communicated; it has the ability to represent the most general computer science data structures such as records, lists and trees; its self-documenting format describes structure and field names as well as specific values; and the strict syntax and parsing requirements allow parsing algorithms to remain simple, efficient, and consistent (*Extensible Markup Language (XML)*, 2006).

XML is also used as a format for document storage and processing, both online and offline, and offers several benefits. XML’s robust and logically verifiable format is based on international standards; its hierarchical structure is suitable for most documents types; it has no licensing restrictions; it is platform independent which makes it adaptable to new technology; and it is well supported by open source software that is freely available (*Extensible Markup Language (XML)*, 2006).

c. Pertinent Extensible Markup Language (XML) Weaknesses

XML is not without its weaknesses. Its syntax is verbose, resulting in higher overhead costs for storage and slower transfer rates. Its formatting of nested data structures requires additional formatting and error checking causing another noteworthy increase in overhead costs. There are also security considerations that arise when XML input is fed from untrustworthy sources and stack overflows are possible (*Extensible Markup Language (XML)*, 2006). Finally, the keystrokes required to input data into XML format on a standard keyboard is not intuitive and can be tedious.

5. Joint Meteorology and Oceanography (METOC) Broker Language (JMBL)

Joint military operations often reveal a lack of interoperability between differing services. In recognition of this, the Joint METOC Data Services Framework (JMDSF) was created in 1995 to integrate all geophysical data requirements of the entire DOD with their primary objective to provide the warfighter information superiority by supplying relevant information within the time constraints of their decision cycle (Wahbum & Morris, 2005). To standardize the requesting and dissemination of this data, the Joint METOC Interoperability Board (JMIB) was chartered by the Navy and Air Force and tasked with addressing interoperability issues (Wahbum & Morris, 2005). The JMIB established the Data Standards Working Group which created the Joint METOC Broker Language (JMBL) to define an XML schema to establish a DOD wide, single interface for requesting and retrieving METOC data. All JMBL development is Java 2 Platform, Enterprise Edition (J2EE) compliant and uses standard Web service protocols such as XML and Simple Object Access Protocol (SOAP).

Once a warfighter has requested data via JMBL as in Figure 27, it is directly returned in one of several available formats, as in Figure 28, allowing the customer to view and overlay multiple data sets using mapping and plotting services without any additional software or plug-ins. The standards within JMBL also benefit software developers as it provides a robust toolkit with application program interfaces (APIs) allowing Tactical Decision Aid (TDA) to link to multiple data sets using the same standard JMBL request and response structures (Wahbum & Morris, 2005). Thus, TDA developers can send a single JMBL request via a single interface and receive multiple data sets from different sources using standard Web services protocols. Another advantage is that this allows developers to take advantage of Object Oriented Programming (OOP) and reuse different web services instead of having to write a new application each time *(Object-oriented programming*, 2006).


```
<RequestList xmlns="metoc:jmcbl:jmbl">
  <Request>
    <InformationType>
      <MetocDataType>
        <Observation>
          <PlatformCode>
            <PlatformList><PlatformId>KEHA</PlatformId></PlatformList>
          </PlatformCode>
          <ObservationParameters>
            <Parameter parameterName="temperatureAir“parameterUnit="degreesCelsius" />
          </ObservationParameters>
          <Time>
            <TimeRange startTime="2003-12-20T01:59:05Z"/>
          </Time>
          <ObservationReportTypeCode>FM-15</ObservationReportTypeCode>
          <ObservationReportTypeCode>FM-16</ObservationReportTypeCode>
        </Observation>
      </MetocDataType>
    </InformationType>
  </Request>
</RequestList>
```


Figure 27. Observation request message formatted in JMBL 3.0 (From Wood & Mathews, 2005).

```
<ResponseList xmlns="metoc:jmcbl:jmbl">
  <Response>
     <DataItem>
       <Time>
         <TimeRange startTime="2003-12-20T01:59:05Z"/>
         </Time>
         <METOCdatadataElementName="temperatureAir“eturnedParameterUnit="degreesCelsius">
            <Value>
              <DoubleValue>8.0</DoubleValue>
             </Value>
           </METOCdata>
           <DataItemStatus dataItemOrderStatus="Data Filled"/>
         </DataItem>
         <ResponseStatus orderStatus="Request Filled"/>
       </Response>
     </ResponseList>
```


Figure 28. Observation response message formatted in JMBL 3.0 (From Wood & Mathews, 2005).

E. COMPUTING THE BALLISTIC CORRECTION (BALCOR)

1. BALCOR Application Data Flow Algorithm and Diagram

The diagram in Figure 29 outlines the steps performed in running the BALCOR in the AUV Workbench and is explained in section 3. Figure 30 is provides to outline of the data flow of the BALCOR application in the AUV Workbench. Appendix A contains a screen capture of the AUV Workbench after is has calculated a BALCOR.

2. Security – FOUO ERM Parameters Plug-In

The AUV Workbench is an open-source tool that can be freely downloaded from the internet. However, this project requires the use of the FOUO ERM 5DOF model to be used in the AUV Workbench. The actual model created in the ERM 5DOF is not FOUO as they are based on the basic laws of physics, however, the parameters contained in this code are considered to be FOUO. In order for the AUV Workbench not to contain FOUO information, the actual parameters in the MunitionBody.java have been replaced with generic, non-FOUO parameters. In order to use the FOUO ERM 5DOF in AUV Workbench, this model with the FOUO parameters can be loaded from the FOUO Savage Defense model archive or another external source.

- With in the running AUV Workbench, the user selects the Munition mission type for the ERM. If it is available, the FOUO plug-in parameters for the ERM are used, if not, the default generic parameters are used (screen shots of the AUV Workbench can be found in Appendix A).
- AUV Workbench executes the Munitionsbody.java which runs the ERM 5DOF model/simulation
- AUV Workbench provides a launch point (latitude, longitude, height above mean sea level) and bearing on which the ERM is to be fired.
- The ERM 5DOF calculates a change in position of the projectile which is added to the launch point parameters providing a new position.
- At this new position the AUV Workbench retrieves environmental parameters that are then used to by the ERM 5DOF to calculate is next position.
- ERM 5DOF simulation will run until the height becomes negative.

Figure 29. BALCOR application's real-time dynamic modeling algorithm using FNMOC's NOGAPS NWP forecasted data.

3. Integrating NWP Data into the AUV Workbench using JMBL

The AUV Workbench's Environmental Module uses a come and get it product services (CAGIPS) consisting of three methods which are the Preloader, Downloader, and Accessor. The preloader constructs a JMBL "RequestList" message illustrated in Figure 30 to request the required environmental data from FNMOC. This requested provides FNMOC the metadata required from their Integrated Stored Information System (ISIS) database. This metadata includes the four latitude/longitude positions of the boundary box, the base reference time of the model run, the model, and the levels for which data was required. Figure 31 provides an example of a partial RequestList message requesting the air temperature in Kelvin at the 4 mb (note: 1 millibar = 1 hectopascal) pressure level from the 1200Z NOGAPS model run.

When FNMOC receives the "RequestList" message, it system extracts the required data out of its ISIS database and writes it in the GRIB file format to its local CAGIPS server. Once the data is populated, a "ResponseList" is constructed providing the requestor a secure Uniform Resource Locator (URL) to where the data are located.

The ResponseList provided from the RequestList in Figure 31 is shown in Figure 32 below.

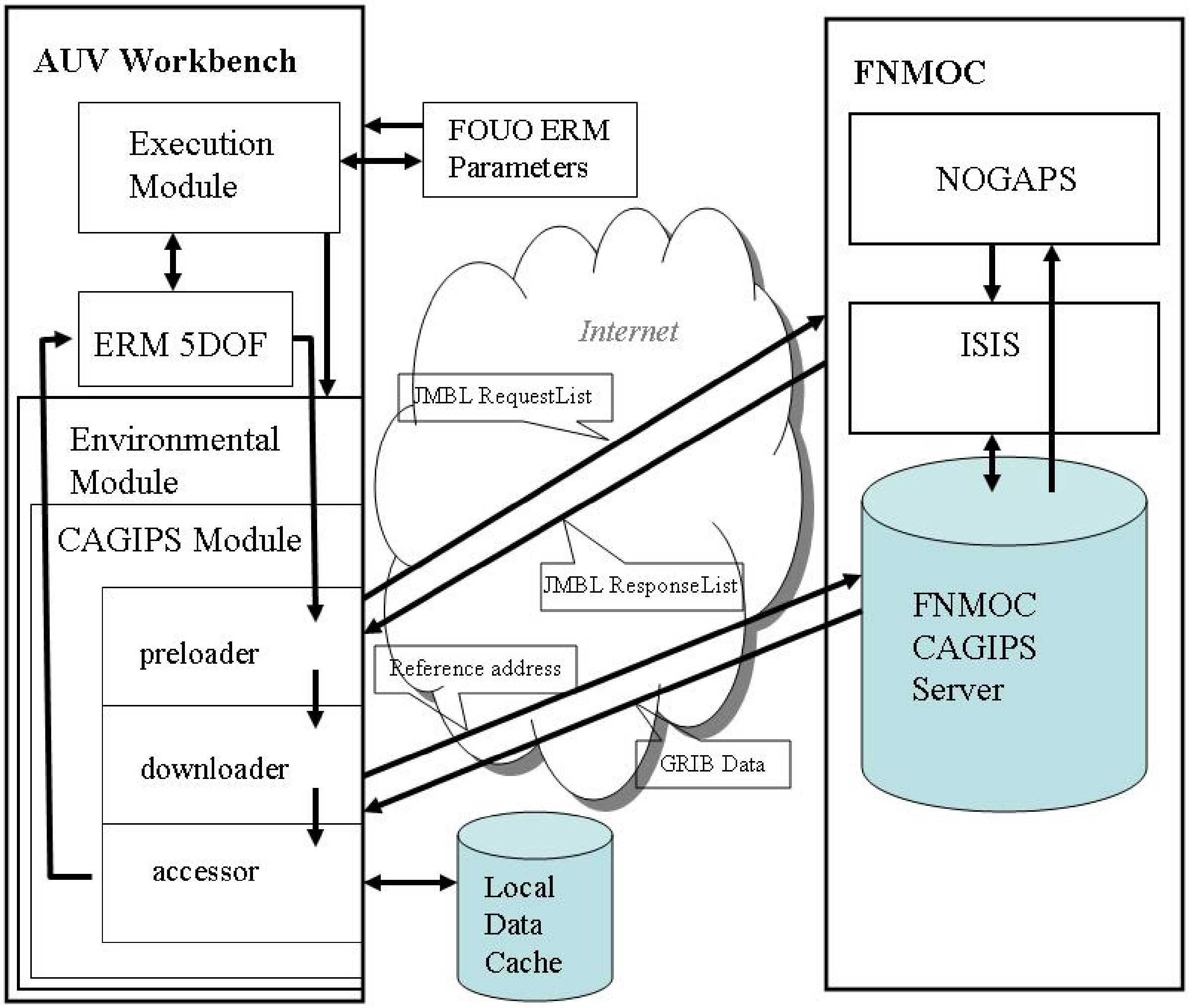

Figure 30. Data flow diagram for BALCOR application.

```
<RequestList xmlns="urn:metoc:jmcbl"
       xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:type="RequestList">
  <Request clientRequestId="12345">
   <InformationType>
    <MetocDataType>
     <GriddedData>
      <GriddedAnalysisForecast />
       <Location>
         <BoundingBox lowerLeftLatitude="32" lowerLeftLongitude="-121"
           upperRightLatitude="34.5" upperRightLongitude="-116.5" />
       </Location>
       <Time>
         <ForecastTime baseReferenceTime="2006-11-03T12:00:00.000Z" forecastPeriod="0" />
       </Time>
      <Process>
         <Process center="058" subcenter="000">
         <ProcessName>NOGAPS</ProcessName>
         <Theater theaterName="global_720x361" />
         <RunTimeCode>RL</RunTimeCode>
         <DataModeCode>F0</DataModeCode>
      </Process>
      <GridParameter>
         <Parameter parameterName="temperatureAir"parameterUnit="degreesKelvin" />
      </GridParameter>
      <VerticalDimension>
         <VerticalDimension lowerLevel="4" verticalDimensionUnits="hectopascals">
         <MasterLayerName>ISBL</MasterLayerName>
     </VerticalDimension>
```


Figure 31. Example of a partial JMBL RequestList data message requesting air temperature in K at the 4 mb pressure level from the 12000Z NOGAPS model run.

```
<ResponseList xmlns="urn:metoc:jmcbl"
  xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:type="ResponseList">
  <Response clientRequestId="12345">
    <DataItem>
      <Format responseContainment="By reference"
        networkAddressName="https://www2.metnet.navy.mil/gridws/grid/NOGAPS/
            2006110312/global_720x361/air_temp/isbr_lvl/4.00/0/fcst_ops/0/32,-121,34.5,-
            116.5/real/deg_K/FNMOC/mb/UNCLAS/ISIS_FORMAT/" />
      <Location>
        <BoundingBox lowerLeftLatitude="32" lowerLeftLongitude="-121"
              upperRightLatitude="34.5" upperRightLongitude="-116.5" />
      </Location>
      <Time>
        <ForecastTime baseReferenceTime="2006-11-03T12:00:00.000Z" forecastPeriod="0" />
     </Time>
       <Process center="058" subcenter="000">
       <ProcessName>NOGAPS</ProcessName>
       <Theater theaterName="global_720x361" />
       <RunTimeCode>RL</RunTimeCode>
       <DataModeCode>F0</DataModeCode>
     </Process>
  <METOCdata dataElementName="temperatureAir" parameterUnit="degreesKelvin">
      <VerticalDimension lowerLevel="4" verticalDimensionUnits="hectopascals">
      <MasterLayerName>ISBL</MasterLayerName>
     </VerticalDimension>
   </METOCdata>
   </DataItem>
```


Figure 32. Example of a partial JMBL data ResponseList message from the RequestList message provided in Figure 31.

Once the response message is received, the requestor, the AUV Workbench’s Environmental downloader accesses the URLs and downloads and decodes the GRIB data. Then the data are ready to be accessed by the Environmental Module’s accessor while running the application.

This application requests the data for the following fields: mean height above sea level, geopotential height, temperature, u winds, v winds, and w winds. Though they are downloaded for future use, W (vertical) winds are not used in computing the BALCOR as they are not properly computed by NOGAPS and are an order of magnitude smaller that u and v (horizontal) winds (Torsten Duffy, personal communications, November 17, 2006).

4. 3D Data Interpolation

The ERM 5DOF model computes the projectile's location every 0.2 seconds in the form of x, y, and h. This data is updates the latitude, longitude, and height position of the ERM. At each of these time steps, Environmental Data accessor uses a data interpolation to accessed a local server where the decoded FNMOC GRIB data is contained and then uses an inverse distance weighted average method to provide the environmental data required. This data interpolator used was provided by NCAR and can be found at http://ngwww.ucar.edu/ngdoc/ng4.4. NCAR's interpolation method calculates the values at a given position using a weighted average, where the weights are determined via inverse proportion to the distances from the known data. Indepth detail concerning the interpolation method used is available at the NCAR website listed above.

5. Computing the Ballistic Correction (BALCOR)

Figure 33 outlines the algorithm for computing the BALCOR. First the munition mission is run in the AUV Workbench using U.S. Standard Atmospheric data parameters. This fires the projectile on a bearing to its maximum range to the 'first' impact point. Next the same mission is run using FNMOC NOGAPS NWP forecasted environmental data and the 'second' impact point is recorded. Next the angle between the launch point and the two impact points is calculated providing the BALCOR using the Law of Cosines (Vallado & McClain, 1997):

$$A = \arccos(\frac{(a^2 - b^2 - c^2)}{(-2bc)})$$

The angle 'A' is then applied to the firing angle off setting the gun by the effects of the forecasted environment.

- Fire the projectile using U.S. Standard Atmosphere, 1976, environmental data and record impact point #1 and compute the distances from the launch point (labeled b on Figure 34).

- Fire the projectile using FNMOC NOGAPS NWP forecasted environmental data and record impact point #2 and compute the distances from the launch point (labeled c on Figure 34).

- Compute the distances between impact point #1 and #2 (labeled a on Figure 34).

- Use the Law of Cosines to compute the BALCOR angle A.

Figure 33. Algorithm used to compute the BALCOR angle (A).

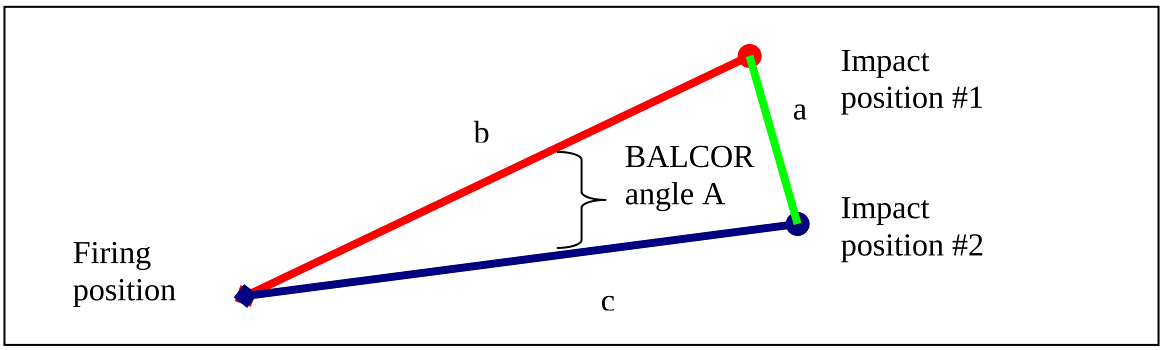

Figure 34. Diagram of projectile impact positions required to calculate the BALCOR. Impact position #1 uses U.S. Standard Atmosphere, 1976 data. Impact point #2 uses FNMOC NOGAPS NWP forecast data.

F. RESULTS

1. Data Benchmark

The total energy budget (TEB) of an ERM is composed of the projectile's PE, KE, and CE. The unit of measurement for this energy is in Joule (J) and for a projectile it is commonly measured in megajoules (MJ). For the following measurements, the projectile launch height and target heights are equal and all numbers are rounded to two decimal places.

PE is calculated from the following formula using the projectile's mass and velocity and the earth's gravity:

$$PE = -mass \cdot gravity \cdot height$$

KE is calculated from the following formula using the projectile's mass and velocity:

$$KE = 0.5 \cdot mass \cdot velocity^2$$

No open source energy measurement of an ERM's warhead was located. This plus the fact that the CE contained in the projectile's warhead does not vary, CE is not taken into account for this project.

In order to measure the effectiveness that NWP has on the ability to increase the range or lethality of an ERM, the amount of energy the ERM can impact onto a target must be measured. This amount of energy must be calculated at two positions: the projectile's apogee, where the projectiles energy will consist of both its PE and KE, and as it impacts its target where all PE has been converted into KE. It is again noted that these calculations do not take into account the projectile's total energy budget because they do not include CE of the explosives in the projectile's warhead. However, the round KE is important if the projectile is to attack a hardened or protected target, since this energy would be used for penetration. Energy lost between the ERM's apogee and impact is due to drag. If the projectile had the ability to maneuver, which the ERM 5DOF does not model, the amount of energy lost would be greater.

	height (m)	mass (Kg)	gravity (m/s)	velocity (m/s)	PE (MJ)	KE (MJ)	TEB (MJ)
Apogee	32,618.5	32.87	9.81	756.4	10.517	9.403	19.920
Impact	0	32.87	9.81	652.7	0	7.002	7.002

Table 7. ERM 5DOF AUV Workbench data benchmark.

2. Energy Data Collection

Originally the data for this experiment was to be collected over the SCORE range. However due to a persistent high pressure system located over the central western region of the U.S., environmental data was collected between Latitude 35 N to 40 N and 165 W to 170 W, due to a long wave trough at the 300 mb pressure level with a corresponding strong jet stream. This system is shown in Figure 35.

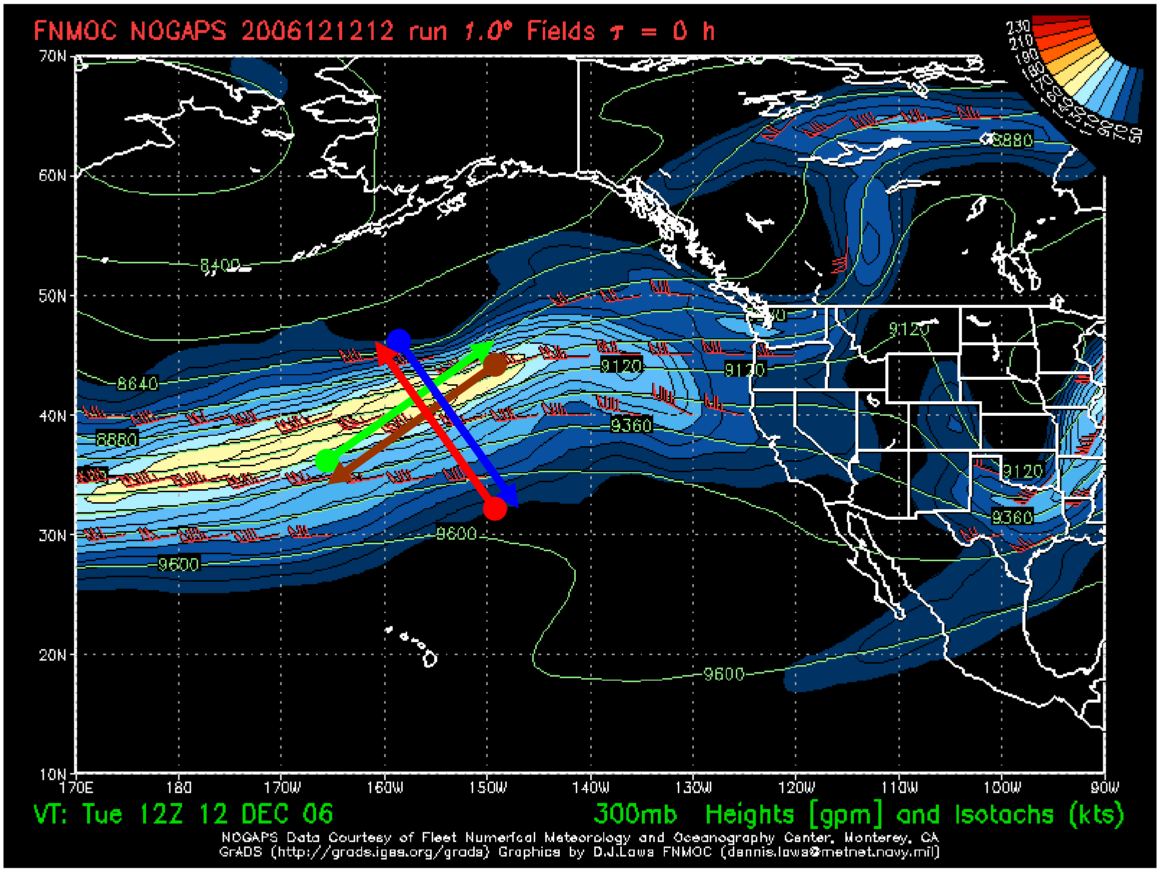

Figure 35. Illustration of 300 mb output data for the 2006121212Z FNMOC NOGAPS model run. The positions indicated are only approximated as their exact location can be found in Table 8 (After [https://www.fnmoc.navy.mil/CGI/PUBLIC/wxmap_single.cgi?area=ngp_ epac&dtg=2006120712&prod=w30&tau=000](https://www.fnmoc.navy.mil/CGI/PUBLIC/wxmap_single.cgi?area=ngp_epac&dtg=2006120712&prod=w30&tau=000)).

This system has a jet max of approximately 80 m/s (155 kts) at the 300 mb height. In order to collect data on the effects of this jet and the environment in this region on the ERM 5DOF, four simulation runs, identified by color on Figure 35 and Table 8, were conducted. ERM 5DOF simulation run ‘Brown’ was against the jet, ‘Green’ was with the jet, and ‘Red’ and ‘Blue’ were across the jet. Data for these simulation results was collected and are shown in Table 9.

Table 8. BALCOR test firing point coordinates as shown on Figure 35.

	Latitude	Longitude	Shot Bearing	Firing Direction
Red	150W	30N	315	North-West
Blue	160W	45N	135	South-East
Green	175W	35N	045	North-East
Brown	150W	40N	225	South-West

Table 9. Collected ERM 5DOF simulation BALCOR data.

	Apogee Height (m)	Apogee Velocity (m/s)	Impact Velocity (m/s)	Maximum Range (m)	BALCOR distance (m)	BALCOR Angle (deg)
Benchmark	32,618.5	756.4	652.7	117,850.1	--	--
Red	32,628.2	774.9	651.1	118,589.7	773.2	.109
Blue	32,629.9	736.1	656.0	116,871.1	1,147.7	.291
Green	32,706.1	739.3	592.3	118,843.9	8,688.1	4.18
Brown	32,627.9	778.6	643.0	117,567.1	1,196.2	.556

3. Energy Data Analysis

Tables 10, 11, and 12 below contain the data collected and analyzed for the various ERM 5DOF simulation runs previously discussed. From the results it is evident that environmental data does have an impact on unguided ERM's trajectory. Specifically, as seen in Table 12, firing the projectile the same direction as the jet stream increases its range by 8.43 percent and firing it against the jet reduces its range by only 2.40 percent. Firing the projectile through the jet produced a very interesting result. Normally it might be believed that crosswinds would have the same effect on the round regardless of which direction the projectile was fired through them. However, because the round has a right-hand spin, the crosswind blowing from the right cause the Red trajectory to acquire a greater velocity and thus a total energy of 27.356 MJ. This is a 1.610 percent increase in total energy when compared to the benchmark data.

Table 10. BALCOR data collection and energy calculation results.

	Height (m)	Mass (Kg)	Gravity (m/s)	Velocity (m/s)	PE (MJ)	KE (MJ)	TEB (MJ)	Mission Total (MJ)
ERM 5DOF Benchmark using U.S. Standard Atmosphere, 1976 environmental parameters								
Apogee	32,618.5	32.87	9.81	756.4	10.517	9.403	19.920	26.922
Impact	0	32.87	9.81	652.7	0	7.002	7.002	
Red: ERM 5DOF trajectory across the jet with environmental data								
Apogee	32,628.2	32.87	9.81	774.9	10.520	9.869	20.389	27.356
Impact	0	32.87	9.81	651.1	0	6.967	6.967	
Blue: ERM 5DOF trajectory across the jet with environmental data								
Apogee	32,629.9	32.87	9.81	736.1	10.520	8.905	19.425	26.502
Impact	0	32.87	9.81	656.2	0	7.077	7.077	
Green: ERM 5DOF trajectory with the jet and environmental data								
Apogee	32,706.1	32.87	9.81	739.3	10.545	8.983	19.528	25.293
Impact	0	32.87	9.81	592.3	0	5.765	5.765	
Brown: ERM 5DOF against the jet and with environmental data								
Apogee	32,627.9	32.87	9.81	778.6	10.519	9.963	20.482	27.277
Impact	0	32.87	9.81	643.0	0	6.795	6.795	

Table 11. BALCOR mission total energy calculations.

	Mission Total Energy (MJ)	Difference from Benchmark (MJ)	Deviation from Benchmark
Benchmark	26.922	--	--
Red	27.356	+.434	+1.610%
Blue	26.502	+.420	+1.56%
Green	25.293	-1.629	-6.051%
Brown	27.277	+.355	+1.319%

It is interesting that the Green trajectory, which was fired with the jet, required the largest BALCOR and had the smallest mission total energy. As expected and as seen in Table 12, this trajectory did have the longest range. The effect of drag on this round was greater that other rounds, but its mission total energy, as shown in Table 11, was the smallest. This demonstrates that the greater the trajectory, the more total energy will be lost to the environment due to drag.

Table 12. BALCOR deviation from benchmark calculation.

	Benchmark	Red	Blue	Green	Brown
Maximum Range (m)	117,850.1	118,589.7	116,871.1	118,843.9	117,567.1
Difference from Benchmark	--	+739.6	-979.0	+993.8	-283.0
Deviation from Benchmark	--	+6.28%	-8.31%	+8.43%	-2.40%

G. SUMMARY

The resulting data from the ERM 5DOF model simulation runs demonstrates that JMBL can be used to communicate FNMOC NOGAPS NWP environmental data and this data has an impact on ERMs. If fully understood, this information can be used by tactical planners to increase the effectiveness of ERMs and other weapon systems that are affected by environmental characteristics.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis supports the ongoing development of ERMs which are being developed to bridge the gap in long-range NGFS that has existed since the retirement of the U.S. Navy's battleships. The purpose of this thesis is to facilitate the use of environmental conditions to increase the range and improve the lethality of the ERMs.

If a BALCOR can be used to produce an optimal trajectory, the projectile retains more total energy at its apogee. This energy then can be used to either increase its range or used to increase its impact on the target. The simulations conducted in this work with the ERM 5DOF demonstrated that TEB and range can be increased. However increasing range comes with the cost of decreasing the ERM's TEB.

This work demonstrated that forecasted environmental data can be retrieved in real-time and used for weapons systems. The ERM 5DOF simulation indicates that intelligently applying environmental data from NWP has the capability to increase range and lethality of weapons that are affected by environmental factors. This approach epitomizes CNMOC's technical and tactical rationales outlined in great detail by CNMOC's strategy letter *Battlespace on Demand: Commander's Intent* (McGee, 2006). No technical showstoppers exist that might prevent the execution of these important capabilities throughout fleet systems.

B. RECOMMENDATIONS FOR FUTURE WORK

The AUV Workbench software can continue to serve as an exemplar for integrating environmental services with real-time tactical and robotic applications. Continue work concerned with connecting environmental data services with fleet systems to produce direct applications should take place. No further 'proof of capability' studies are required, since these capabilities are in existence today. Specific recommendations are listed below.

1. ERM 5DOF

- Although the 5DOF simulation was specifically designed to be unguided, actual ERM have GPS/INS guidance systems and a useful improvement will be to add a control function to simulate a guidance system.
- Conduct further comparison and testing against operational data.

2. AUV Workbench

- Rederive the developed equations of motion in the 5DOF model to match AUV Workbench nomenclature.
- Improve the existing ERM 5DOF simulation by better modeling the projectile's rocket-boost and mass burn.
- Incorporate Coriolis Force effects.
- Apply this application to other modeled projectiles and aircrafts in the AUV Workbench
- As Tomahawk missiles, artillery, UAVs, etc. operate at lower altitudes, it would be practical to use higher-resolution mesoscale model data from FNMOC's COAMPS model.
- Replace the ERM 5DOF with the actual BTERM, ERGM, and LRLAP 6DOFs created by the respective defense contractors and calculate the environmental effects of these high-fidelity models.
- Use existing SCORE terrain data to create a 3D visual tool for NGFS.

3. JMBL

Recommend that FNMOC fully embrace JMBL for all environmental data communication and create an online JMBL catalog with examples of how to request data. Communicating environmental data purely through JMBL, vice having to access FNMOC's CAGIPS server, will positively impact the architecture designed for this application and allow it to retrieve data using the existing methods from other providers of environmental data such as AFWA. JMBL data can then be used for other applications such as BALPARs, BALWINS, etc.

4. Fleet Development

A U.S. Navy-wide examination of weapons system, combat control systems, and TDAs to utilize forecasted environmental data via net-centric GIG compatible web services. The AUV Workbench's implementation of this project is a proof of concept that can be further developed to support:

- Integrated Battlegroup/Battlespace mission planning.
- Visualized flight profiles and projectile trajectories in 3D battlespace for air/space coordination and fire deconfliction.
- Assessing the uncertainty associated with meteorological environmental factors. Allowing shipboard mission rehearsal of extended-range flight profiles using modeled environmental data. Providing the ability to adjust tactical firing settings and weapon presets to account for environmental conditions.

The final recommendation is for the U.S. Navy to assert ownership of technical and engineering data regarding all aspect of ERM design and development so that currently existing propriety restrictions no long inhibit the development of effective tactics and creation of other useful products.

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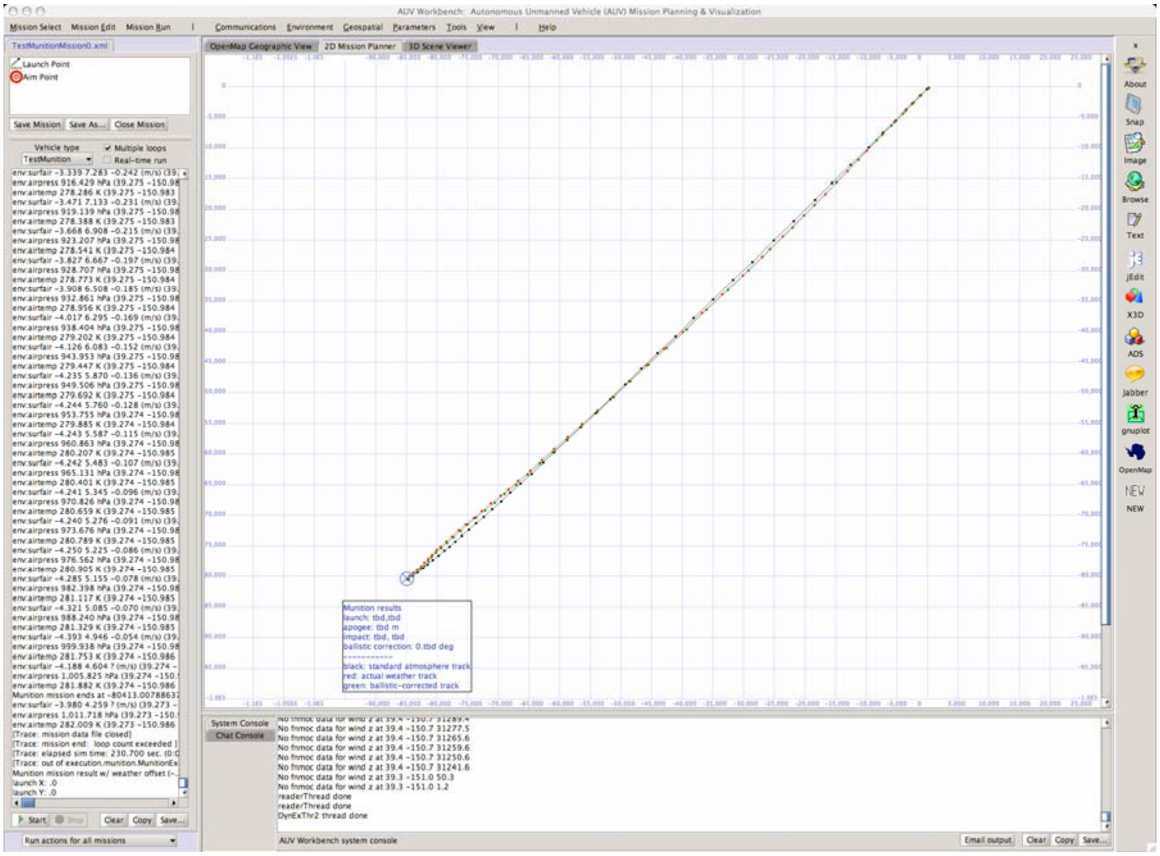
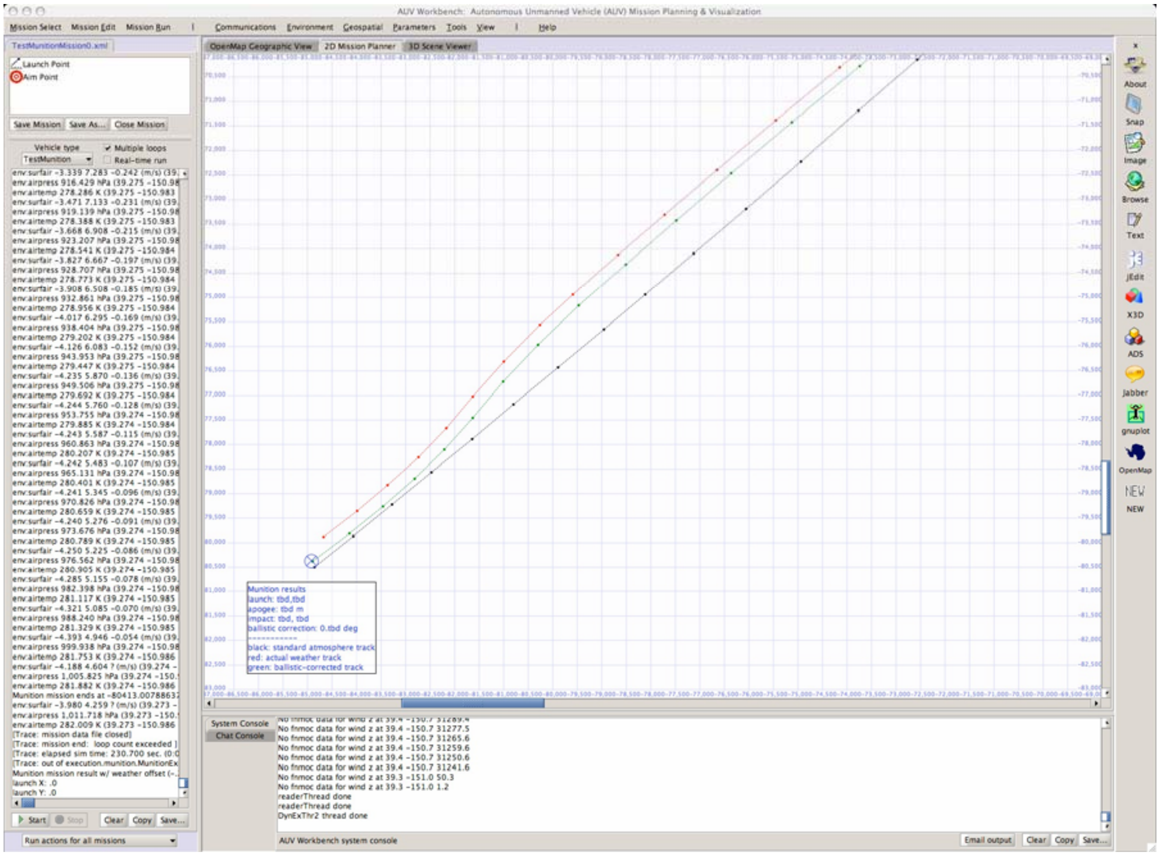
APPENDIX A

Below are screen shots of the AUV Workbench after it has calculated a BALCOR.




AUV Workbench: Autonomous Unmanned Vehicle (AUV) Mission Planning & Visualization
Munition results
launch: tbd,tbd
apogee: tbd m
impact: tbd, tbd
ballistic correction: 0.tbd deg
black: standard atmosphere track
red: actual weather track
green: ballistic-corrected track

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